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CONTENTS

	PAGE
The Production of Oil from the Fields of Southwestern Iran. By H. S. Gibson, C.B.E.	374
The U.K. Petroleum Industry in War. By Sir Andrew Agnew, C.B.E.	403
Vaporization in Furnace Tubes. By G. Baars	417
Obituary: W. H. Park	443
Abstracts	145A
Book Reviews	182A
Books Received	183A
Applications for Membership or Transfer and New Members	i–iv

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H. S. Gibson, C.B.E.

Redwood Medallist 1948.

[*To face p. 373.*

THE INSTITUTE OF PETROLEUM.

AN Ordinary General Meeting of the Institute of Petroleum was held at Manson House, 26 Portland Place, London, W.1, on Wednesday, March 10, 1948, the President, Sir Andrew Agnew, C.B.E., in the Chair.

The Minutes of the preceding meeting of the Institute were read by the Publications Secretary (Mr. George Sell), confirmed, and signed.

The President referred with regret to the absence of Mr. F. H. Coe, the General Secretary of the Institute, who was in hospital.

The Publications Secretary read the names of those elected to membership of the Institute since the last meeting and gave notice that, at the Annual General Meeting on April 30, consideration would be given to and, if thought fit, a resolution would be passed for the alteration of certain existing By-Laws; and that the proposed alterations were available for inspection by any member during the normal business hours.

MR H. S. GIBSON, C.B.E., M.A., F.Inst.Pet., who was received with prolonged applause, then delivered the following paper on "The Production of Oil from the Fields of Southwestern Iran." Before commencing the paper, the author explained that when he was asked nearly a year before to give this paper he had some difficulty in deciding which aspect to deal with, because it was manifestly impossible to cover the entire subject in a short space of time. Finally he decided to deal with the mechanism of oil recovery from the reservoir rock and the production-control methods employed, since he had himself found these to be of continuous interest throughout the twenty-five years he had spent on the oilfields, and therefore hoped that they would also prove of interest to the members of the Institute.

The interest probably lay in the fact that no one could say with absolute certainty what happens in these huge limestone reservoirs, and evidence obtained from observation of the field's production and from carefully designed experiments must be pieced together to build up the complete picture. Experiments are often very difficult to design and carry out owing to the time factor and the absolute steadiness of the reservoir temperature.

The author then made it clear that the deductions drawn from the available evidence were entirely his own, and although in the main accepted by his colleagues, the latter did not necessarily subscribe to them completely.

THE PRODUCTION OF OIL FROM THE FIELDS OF SOUTHWESTERN IRAN.

By H. S. Gibson, C.B.E. (Fellow) (Redwood Medallist 1948).

Introduction.

The first field discovered in Southwestern Iran was Masjid-i-Sulaiman, which began producing in 1911, and to date has produced just over 120 million tons of crude, which makes it the fourth largest single field in the world, the three larger being, of course, East Texas, the Lagunillas field in Venezuela, and the Balakhany–Sabunchy–Romany field of Baku. Masjid-i-Sulaiman is still producing about 3¾ million tons a year (or 29 million barrels) and although a total of 229 wells have been drilled, the greatest number ever used for production at one time was 31. With so many wells available for observation purposes, and the length of time it has been producing, far more is known about Masjid-i-Sulaiman than any other of the fields of Southwestern Iran, and the development of control and the study of the mechanism of production of the Iranian fields is in effect a history of this field.

The value of the experience gained at Masjid-i-Sulaiman is already shown in the Haft Kel field, which has now produced just over 100 million tons of oil. At Haft Kel only 42 wells have been drilled into the reservoir, and of these the maximum number on production at one time has never exceeded eighteen.

The Reservoir Rock.

The reservoir rock of the oilfields of Southwestern Iran is a marine fissured limestone named after Asmari Mountain (Fig. 1), where the limestone outcrops a few miles away from Masjid-i-Sulaiman as a typical whaleback structure. The mountain is very similar in shape and size to the Masjid-i-Sulaiman reservoir, and provides a full-scale model which can be examined at leisure.

The limestone is Upper Oligocene to Lower Miocene in age, and is about 1000 ft thick. When a well drills into the rock, no appreciable production is obtained until a fissure is penetrated, no matter how richly oil-bearing the cuttings appear to be. The individual capacities of the wells range from 500 to 2000 tons per day each, which explains why more than 31 wells were not required on production at any one time. At first, drilling was confined to the area of the discovery well, which is located at about the mid-point of the southwest flank of the structure in the district known as Naftun, as shown in Fig. 2.

At first it was not clear which was the producing formation, but in 1918 the Asmari limestone was recognized as the reservoir rock. From that year onwards certain of the wells of high-rock elevation ceased to produce oil and yielded only gas, showing that a gas dome had formed and that there was a gas–oil interface which was falling with production. The position of this interface, or gas–oil level, was shown approximately by the elevation of the bottom of the wells going to gas. The gas pressure could not be

measured, because none of the well-head fittings could carry the pressure. In 1923, a well fitted with high-pressure fittings was drilled into the gas dome, and from its pressure and the pressure in the oil zone it became possible to calculate the position of the gas–oil level, which was found to be falling about 15 ft for each million tons of crude produced.

By the same year, wells had been drilled towards the northwest in the district known as Naftak, and the area from which production was drawn was being slowly extended in that direction. In 1921 it had been shown that the closed-in-pressure of the first well drilled at Naftak was affected by the opening and closing of wells at Naftun some three miles away, thus proving extreme freedom of connexion through the reservoir.

FIG. 2.

MASJID-I-SULAIMAN PRODUCTION WELLS IN 1923.

EDGE WATER MOVEMENT.

From the time when production had first begun, some concern was felt at the lack of knowledge of the position of the edge water and its movement. It was remembered that in other limestone fields, water had been known to rise with great rapidity, *i.e.*, at a rate corresponding to the fall of pressure expressed as the differential head of oil and water. Wells were successively located deeper and deeper down the southwest flank until in the first half of 1924 a well reached water after drilling past a good oil show. The position of the oil–water contact in the well was carefully measured and closely observed. It was quickly established that the oil–water level was not rising at the rate to be expected from the reservoir being in free connexion with an external water table; in fact, for over two years there was no definite indication of any rise at all. This was, of course, a great discovery, and showed that the crude oil reserves were very considerable.

Several other wells were soon drilled to edge water in other parts of the field, including one in the northeast flank, and by the end of 1926 the general position of the edge water round the reservoir was known. Many of the limestone samples obtained from below the oil–water level were found to contain appreciable quantities of oil.

By 1927, production was being drawn along practically the whole of the southwest flank, and wells had been drilled along the greater part of the northeast flank, plans being in hand to draw protection from them at an early date. All the wells which had gone to gas, or were showing signs of doing so, had either been mudded-off or fitted with high-pressure fittings that enabled them to be shut in. The value of gas conservation was fully appreciated, and no oil was drawn from any well producing gas in excess

of that held in solution in the oil at the bottom of the casing, with the result that the gas-dome pressure was falling by less than 2 p.s.i. per annum.

Various samples of limestone obtained from wells had been from time to time examined and found to have porosities varying from 8 to 12 per cent, but their permeabilities were very low. Although these samples of porous limestone contained appreciable quantities of crude, it was generally accepted that the production of the field was not dependent on the porosity of the limestone, but came from pores, channels, and fissures of another order of size. As there was still no sign of edge-water encroachment, the reservoir had come to be regarded as a closed tank from which crude could be drawn at any desired rate, so freely did the

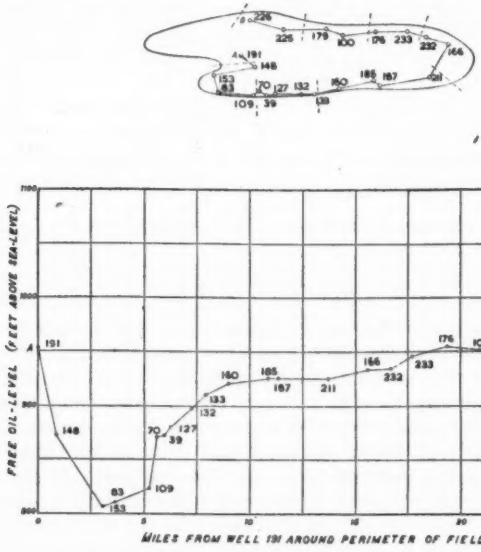


FIG. 3.

MASJID-I-SULAIMAN FIELD. FREE OIL LEVELS ON 4.10.47.

wells flow and so slightly did their producing rates decline. A drilling programme was bringing in new producing wells at the rate of 15 to 20 a year.

In August 1927 a very serious occurrence took place. Well No. 56 at the Naftak end of the southwest flank began to produce salt water in considerable quantity, although the bottom of the well was some 200 ft above the estimated oil–water level. Tests soon showed that the rise of water was very local, for water observation wells on either side, one two miles away, and the other a mile and a quarter, showed no change of oil–water level either up or down. Several wells in this area had only recently been connected to production, and as all the wells drilled there had proved to be good producers, an off-take comparable with that drawn from the original producing area was allocated to them. The effect of this

production on the pressure in the reservoir is shown in Fig. 3. This diagram shows the free oil level as measured in non-producing wells located round the perimeter of the field. Free oil level is the height above sea level at which the oil stands in the casing of a well which is not being drawn upon for production. The column of oil in the casing is in balance with the pressure in the oil zone of the reservoir, and it is in effect a sensitive pressure-gauge. In wells of high-ground elevation, the column of oil does not reach the well-head and the level is measured by dipping; in low-elevation wells the oil column reaches the well-head and exerts a pressure there. To obtain the free oil level this pressure is converted into an equivalent height of oil and added to the elevation of the well-head. The free oil level is at once a measure of the pressure in the oil zone, and, under a common gas dome, an indication of the relative gas–oil level.

The pressure in the vicinity of Well No. 56 was nearly 40 p.s.i. lower than in the producing area in the middle of the southwest flank, and 65 p.s.i. lower than on the opposite flank. It was immediately realized that this pressure difference must be the cause of the water entering the well, and production from the Naftak area was at once closed down. It was assumed that the connexion in the water zone was as free as in the oil zone, and that since under equilibrium conditions 1 p.s.i. difference in the oil zone required a rise of between 5 and 6 ft of oil–water level to balance it, a rise of 250 ft in oil–water level could easily be accounted for. There was no explanation, however, of the fact that with such a free connexion assumed in the water zone the oil–water level on either side within two miles was unaffected, although the pressure in the oil zone there was 20 p.s.i. down.

At the same time it was apparent that connexion was not as free throughout the reservoir as had been supposed, otherwise a reduction of pressure in one section of the field such as had occurred would not have been possible.

In order to avoid similar occurrences in the future, it was decided that the reservoir would have to be treated as a unit and a uniform pressure maintained in all sectors, the argument being that under a uniform pressure the oil–water level would be uniform. Off-take therefore would also have to be so distributed that the fall in pressure due to production must be uniform over the whole field.

This was a very important step forward in reservoir control, and to put it into effect it was necessary to have a continuous record of the pressures all over the field, for which special observation wells would be necessary. It was noticed from the free oil levels shown in Fig. 3 that in some parts of the reservoir the pressures of adjacent wells were in close agreement, and that in others there was considerable difference. The inference was drawn that between the former there was very free connexion and that between the other wells there was a certain amount of restriction to flow. Although gas–oil level was well above the highest point of the pre-Asmari core of the structure, and therefore the migration of oil from one flank to the other could be reasonably expected, this did not appear to be taking place to any appreciable extent. It was therefore concluded that the reservoir was divided more or less effectively into sectors or compartments round the perimeter inside which the connexion between wells was so good that they were self balancing, and it did not matter from which well, or wells, production was drawn. The boundaries of these compartments are

shown in Fig. 3 by short lines drawn across the gradient lines connecting the wells.

The next step was to balance up the field, and at the same time begin to find out what proportion of the total production could be drawn from each compartment to give a uniform-pressure drop in the oil zone throughout the reservoir. This was done by trial and error, the Naftak sector being shut down for the first year. It soon became obvious that the field is far from being uniformly productive. The Bibian sector, for example, produced about 50 per cent of the total crude, although the volume of the reservoir rock there is only 20 per cent of the field. It was later found that the allocation to the Naftak sector should have been 10 per cent.

Well No. 56, which had produced water, continued to do so whenever tested for the next eight months, but after nine months was water-free, and within fourteen months was back on continuous production with no trace of water. The oil–water level in that sector returned to its normal position and has remained normal ever since.

The result of the rise of water at the northwest end of Naftak was that the use of observation wells and the system of control by uniform pressure drop over the whole reservoir became firmly established.

The process of balancing pressures and fluid levels over the whole reservoir took just over four years to complete, during the course of which it was proved that the northwest pitching end of the structure, the Asiab area, was practically non-productive except for one well. During the drilling of wells, it had become increasingly obvious that production was obtained only if an open fissure was penetrated. Sometimes a well would drill only 2 or 3 ft into the limestone before obtaining large production; at other times 300 ft or more of limestone would be drilled without any sign of production, and then suddenly the well would be a producer.

Although it was felt that all the oil produced came from fissures, the possibility of production coming from porous limestone was never entirely ruled out, so in 1930 an extensive investigation of the reservoir rock was undertaken. Continuous cores had recently been taken in two wells throughout the full thickness of the limestone, and in addition several hundred rock samples from other wells situated in all part of the structure were examined. The samples were closely examined for evidence of honeycombing, but none was found.

The degree of dolomitization of 91 samples was also determined, but no direct relation between dolomitization and porosity could be obtained. One interesting fact discovered was that nearly every sample of porous limestone examined contained water, the average being about 15 per cent of the pore space. It was also noted that in addition to the larger fissures some of the cores examined contained very fine cracks almost invisible to the naked eye. When a freshly obtained core was washed, the position of these cracks was indicated by the efflux of oil.

The conclusions reached by this investigation were that whilst the limestone was to some extent porous and permeable, production was not dependent on porous or cavernous limestone, but upon open fractures, and that production depending on the permeability of porous limestone under reservoir conditions was so low as to be entirely negligible.

Production from Porous Limestone.

About a year later, however, an incident occurred which threw considerable doubt on the above conclusion, and re-opened the whole question of the possibility of production from porous limestone.

The sector on the northeast flank adjacent to Asiab was the last one to be brought on production to complete the balanced off-take from the field. It was known to be a small sector, and only one well, No. 245, was connected. No. 245 was apparently a normal well, capable of producing about 1000 tons per day, but it was started on steady production at only about one-third of this quantity. In spite of this low off-take, within eleven days the gas–oil level in its vicinity had fallen an average of 85 ft instead of a maximum anticipated fall of 2 ft. The well was immediately closed, and within a month the gas–oil level was completely restored. The sequence of gas–oil level movement is shown in Fig. 4.

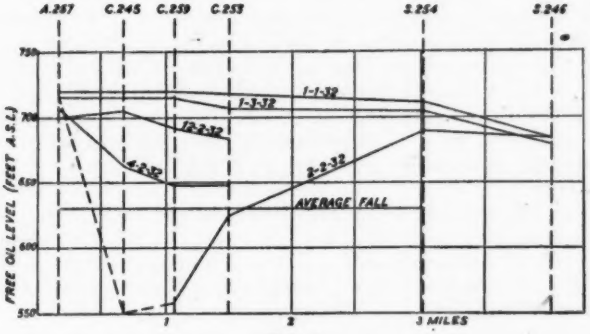


Fig. 4.

FALL OF FREE OIL LEVEL AT C.245 IN FEBRUARY 1932.

The well was then brought on to production very slowly, and it was found that an off-take of 150 tons per day kept the pressure of that zone in equilibrium with the remainder of the reservoir. At this rate the fall of gas–oil level was approximately one-fifth of a foot per day, instead of 8 ft per day for the initial production rate of 330 tons. This difference could only mean that although the well was supplied with oil from a fissure, the fissure was replenished from a source from which the rate of flow was limited. Assuming that the additional 180 tons per day came entirely from 7·8 ft depth of fissure space, then one-fifth of a foot would supply 4·6 tons, and therefore of the 150 tons per day steady production it appeared that 145·2 tons, or 97 per cent, came from the pores of the limestone. This is a minimum value, for if during the heavy initial withdrawal of oil any migrated into the area from adjacent sectors, or if any was produced from porous limestone (which was quite likely), then the amount obtained from the fissures must have been correspondingly less than 180 tons per day.

It had already been noticed that when the off-take of oil from the field was suddenly increased, there was a tendency for the gas–oil level to fall more rapidly for a short period, and conversely, when suddenly reduced,

for the rate of fall to decrease for a time. It now began to look as though this effect might be due to some of the oil coming from porous limestone, in spite of the fact that all the samples of rock examined had appeared so compact and had had such a low permeability that it did not appear possible.

It is probably advisable at this point to consider the behaviour of the very fine cracks in the limestone mentioned on page 378. Some of these were so fine that it would be quite conceivable that gas bubbles formed in them with reduction of pressure below saturation could not move upwards towards the gas dome, but would remain *in situ*, thus causing an equal volume of crude to be expelled into a free flowing fissure or channel. Such fine cracks should, by their behaviour, be classed as pore space. Pore space is therefore best defined by its behaviour, and not by its origin or shape. This definition is therefore—Pore space is that space within the reservoir from which gas bubbles formed by reduction of pressure do not migrate upwards under the influence of the density difference between oil and gas. Similarly, fissures may be defined as spaces in the reservoir from which oil drains by gravity and is replaced by free gas from the gas dome.

A line of attack on the problem of production from pore space was suggested by a visit to Asmari Mountain, which, as stated earlier, is a full-scale model of the Masjid-i-Sulaiman reservoir. On the mountain, two facts were very obvious, first, the infrequency of open fissures over a great part of the mountain, and secondly, the very small width of these fissures. These two points together suggested that the total space available in fissures for the storage of oil in the Masjid-i-Sulaiman reservoir was quite small. The first point was supported by the distances the various wells had to drill into the limestone before striking a fissure, but the second was rather more difficult to check. Calculation showed that fissures ranging in width from one-tenth to one-twenty-fifth of an inch would be adequate to supply wells of the size of those at Masjid-i-Sulaiman, on the basis of the known bottom-hole differential pressures. These bottom-hole differential pressures had been measured some time before, the procedure being to measure the pressure at the bottom of a hole with the well closed, and with it flowing at various rates. The greater the rate of flow, the lower was the pressure at the bottom of the well, the difference between this pressure and the pressure with the well closed being the differential required to deliver that quantity of oil into the well.

As a certain amount of doubt existed regarding the validity of the method of calculation of fissure widths, it was decided to build an artificial fissure to check the method.

The apparatus (Fig. 5) consisted of a circular concrete basin 14 ft in diameter and 18 in deep, the floor being as level as it was opssible to make it, with a 6-in pipe running downwards from the middle representing the well. A circular block of concrete 10 ft in diameter was then cast in contact with the floor of the basin and arranged so that it could be lifted away from the floor of the basin to form a parallel-sided gap or fissure. The lifting of this block was carried out by six differential-screw jacks built in the concrete block. The basin was filled with water, which was drawn from the circumference radially through the fissure and down the pipe by a pump, the discharge of which was returned to the basin. The pressure drop in the

fissure was measured by a series of manometers set in the concrete block along a radius. Tests were carried out with the fissure set at widths ranging

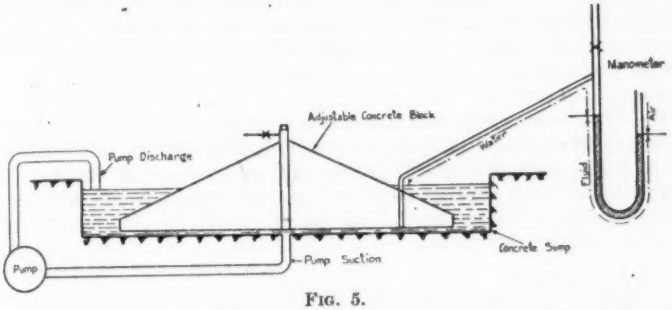


FIG. 5.

APPARATUS FOR STUDY OF RADIAL FLOW BETWEEN PARALLEL PLANES.

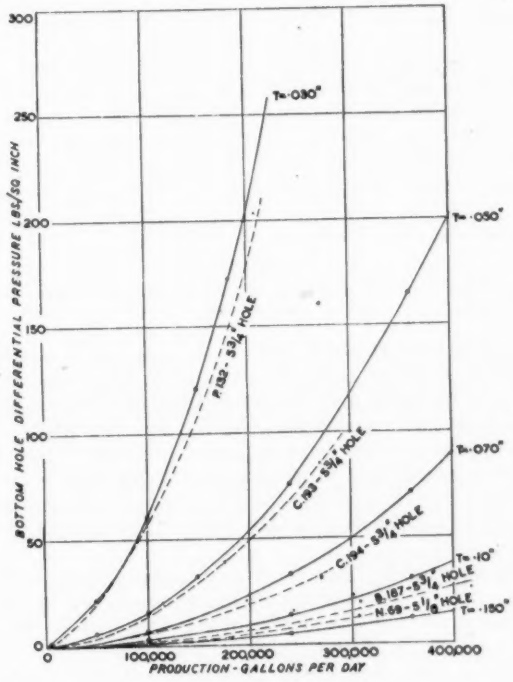


FIG. 6.

BOTTOM-HOLE DIFFERENTIAL PRESSURE PRODUCTION CURVES, ¼-IN HOLE.

from one-fiftieth to one-fifth of an inch, the results being converted to values equivalent to reservoir crude.

The experiments confirmed that the method of calculation of fissure widths from bottom-hole data was sufficiently accurate for all practical purposes. A set of curves giving production against bottom-hole differential pressure for various fissure widths was then calculated, and they are given on Fig. 6, together with measured bottom-hole differential pressure–production curves of wells which are known to have penetrated only one fissure.

The two sets of curves correspond very closely, and it may be stated with a reasonable degree of confidence that the fissures feeding producing wells range from about one-fiftieth to one-fifth of an inch in width. These fissure widths give support to the evidence from Asmari Mountain that fissure space available for the storage of oil in the Masjid-i-Sulaiman reservoir may be quite small.

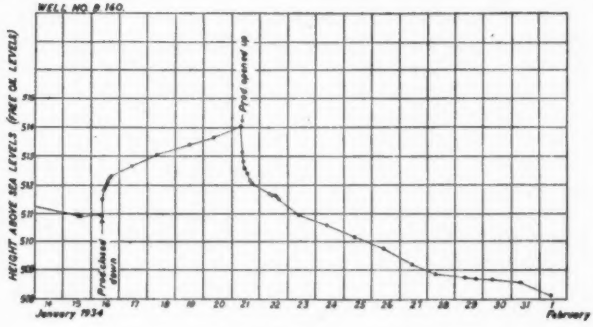


FIG. 7.

MOVEMENT OF FREE OIL LEVEL AT BIBIAN DURING TOTAL SHUTDOWN OF PRODUCTION.

A very interesting fact which emerged from the artificial-fissure experiments was that about one half of the total pressure drop into a well occurs within 18 in of the hole, and that more than 95 per cent occurs within 50 ft of the well. This means that unless a well has penetrated a fissure which behaves more or less as an extension of the hole, the bottom-hole differential is very unlikely to be able to cone up edge water unless the water is within say 50 ft, and also that the pressure reduction at the foot of a well is applied to only a very small volume of limestone in the immediate vicinity.

An opportunity to find out if an appreciable quantity of crude was carried in the fissure system of the Bibian Area occurred in January 1934. Fissures occur much more frequently in this area than in any other, and the production is much greater, being, as mentioned earlier, about 50 per cent of the total field off-take from 20 per cent of the reservoir. All the producing wells were closed simultaneously and readings of the free oil and oil–water levels taken at frequent intervals. The record of the free oil level in one of the observation wells (which can for all practical purposes be taken as the gas–oil level) is given in Fig. 7.

Gas–oil level had been falling uniformly over the field at about 2½ in per

day, but within an hour of shutting down, a rise of 10 in had taken place. After this the rise continued at about 4 in per day for five days (further time could not be afforded for a continuation of the test) without any sign of a falling off in the rate. The initial rapid rise is interpreted as the differential head required to provide a gradient for the flow of crude from the vicinity of the observation well to the producing wells. The steady rise thereafter might be due to oil draining down from the gas dome, or to oil continuing to be expelled from porous limestone below gas–oil level, or to migration from one of the other producing sectors. The fact remains, however, that the fissures were filling up at the rate of 4 in per day.

When production was re-opened again simultaneously all over the area, there was an immediate fall of just over 12 in for the establishment of the flowing gradient, and then for about a day a fall of 8 in. Assuming that on this first day after recommencing production there was no change in the supply to the fissures, *i.e.*, that it continued at 4 in per day, the whole of the production was being supplied by 8 in plus 4 in equals 12 in of oil column in the fissures, so that, under normal steady conditions with a fall of 2½ in per day, 20 per cent of the oil came from the fissures and 80 per cent from porous limestone.

A similar test at a later date on a smaller producing area gave very similar results. Unfortunately production requirements do not permit oilfields to be shut down for lengthy periods (or even for short ones).

With the growing evidence that porous limestone apparently plays a very large part in the production of crude, a re-examination of the reservoir rock was undertaken.

The first step was to obtain some idea of the distribution of porosity. Fortunately it was noticed that a close relationship existed between the colour and the porosity of various limestone samples, and it thus became possible to make an approximate estimate of the distribution of porosity by visual examination of samples, which greatly facilitated what would otherwise have been a very laborious task.

The colourization is apparently due to the adsorption of asphaltic material on the walls of the pores, and the greater the porosity the lower the surface–volume ratio, and therefore the greater the amount of asphaltic material available from the oil per unit of area. This heavy material is adsorbed on the walls of the pores to such an extent that the total oil extracted from a sample of limestone has a higher density than normal crude. Although limestone is not preferentially wetted by oil it does adsorb the heavier material present in the crude, in fact, it was found by experiment that it was as effective as absorbent charcoal in this respect.

By visual examination it was found possible to classify all samples of limestone into four types, the details of which are tabulated below in Table I.

There is a definite relationship between the porosity and permeability of the limestone, for an almost straight line is obtained when the one is plotted against the other on semi-log paper. The permeabilities in Table I are taken from this graph at the porosities given. It will be noted that the porosity seems to depend upon the degree of recrystallization, but even when completely recrystallized the pore spaces are so fine that they bear no resemblance to even the finest-grained sandstone.

TABLE I.

Asmari Limestone Classification.

Types.	Visual characteristics.	Average porosity (approx.).	Average permeability (millidarcys).	Microscopic characteristics.	Degree of recrystallization.
Type 1	Dark grey to light grey and fawn limestones, compact and shiny.	2%	0·00005	Very fine grained, rather marly, fossils well preserved.	Practically nil.
Type 2	Light grey, fawn and light brown limestones, compact.	5%	0·0007	Fine grained, more crystalline and less marly than Type 1. Fossils well preserved.	Negligible.
Type 3	Brown and sometimes light brown limestones, rather granular with some visible voids.	10%	0·05	Rather coarse-grained crystalline limestones. Fossils often destroyed or poorly preserved.	Considerable.
Type 4	Brown and dark brown limestones; granular, with many visible voids.	15%	0·5	Coarsely grained crystalline limestones, only rare traces of fossil remains.	Almost complete.

Micro-photographs of the four types are given in Fig. 8.

Occasionally samples of limestone having a porosity of as much as 20 per cent are found ; the permeability of these is about 10 millidarcys, which is still far less than that of the average sand field, where the permeability generally runs from 50 to 500 m.d. Comparing these values with those of Asmari limestone there is little wonder that earlier opinion had been that the porous limestone was a negligible factor in the production of oil.

The next step was to examine samples from wells which had drilled completely through the reservoir rock and assess the porosity distribution on the basis of the four types of limestone. The result is given in Fig. 9, in which, for the sake of clarity, the two lower porosity types and the two higher are grouped together. The overall picture shows the upper 400 ft of the reservoir to contain considerably more pore space than the lower 600 ft. The lower 600 ft is composed of thin, marly limestones interbedded with grey marls, the proportion of the latter increasing with depth. The upper 400 ft is much more thickly bedded, being almost massive in character. The beds of limestone and marls constituting the Asmari Limestone are not continuous, but appear to be more or less lenticular in form, the only bed which appears to be continuous throughout the reservoir being the middle Anhydrite which tends to isolate the lower 400 ft from the upper 600 ft.

Having obtained some idea of the porosity distribution in the field, it

now became necessary to find out if oil really could be obtained from the porous limestone. A piece of limestone of about 10 per cent porosity was filled with crude oil and saturated with gas at 600 p.s.i., the initial saturation pressure in the crest of the Masjid-i-Sulaiman reservoir. The pressure was then reduced, at the rate of 100 p.s.i. per hour, down to atmospheric pressure. Oil was expelled from this limestone and was measured. The results are given in Fig. 10 in the curve marked *A*, expressed as a percentage of the total oil in the sample. A total recovery of only 25 per cent was obtained

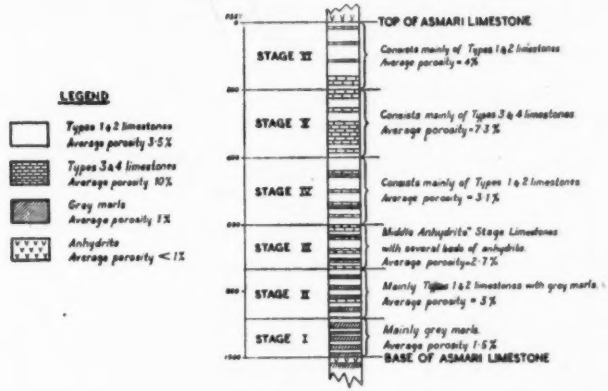


FIG. 9.

ASMARI LIMESTONE, MASJID-I-SULAIMAN. LOG SHOWING GENERALIZED LITHOLOGY.

and of this four-fifths came out of the limestone in the first 200 p.s.i. pressure drop.

The experiment was repeated with a second sample of limestone and the results were given in curve *B*; here only 20 per cent recovery was obtained, although the porosity of the sample was slightly higher than that of the first one, and three-quarters of this came out in the first 300 p.s.i. pressure drop.

A calculated curve, showing the amount of oil that might be expected to be expelled, based on the volume of gas released from solution with reduction of pressure, is also shown for comparison. Curve A is in reasonable agreement with it down to 20 per cent recovery, and it may therefore be assumed that the oil was accompanied by its gas which had come out of solution. At 18 per cent in curve A, and 8 per cent in curve B, the flow of oil began rapidly to diminish and the amount of gas to increase, *i.e.*, the gas–oil ratio increased.

The remarkable thing about these results, especially curve *B*, is that they are practically identical with the results obtained with oil sands of very much higher permeability. The mechanism of expulsion is that known as "dissolved gas drive" which in sand fields gives a maximum recovery of oil in place of only 15 to 25 per cent, the porosity of the sand having very little effect on this amount. From this experiment with limestone, it

appeared that the very much lower permeability had negligible effect also, though one would have expected that with lower permeability and a consequent higher surface–volume ratio in the pores, a larger amount of oil would have been retained on the walls of the pores as an unrecoverable film.

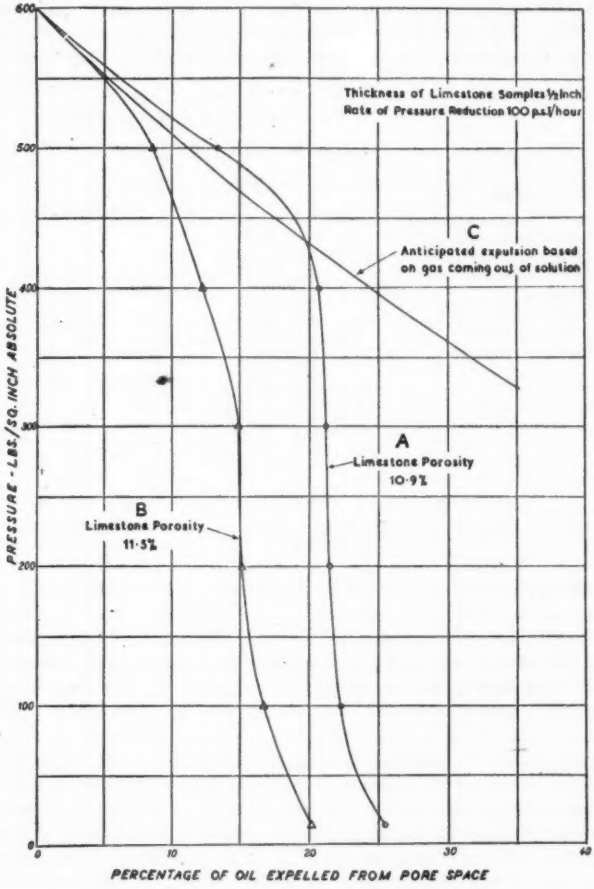


FIG. 10.

RECOVERY OF CRUDE FROM POROUS LIMESTONE.

The rate of pressure drop on the limestone in this experiment was very rapid compared with conditions in the reservoir, where the pressure falls at the rate of about 1·7 p.s.i. per month. Whether this very much slower rate would increase or decrease the recovery it is impossible to say. If the rate of fall is comparable with the rate of diffusion of gas in solution in the

crude, then the recovery would be decreased. Diffusion, however, is an exceedingly slow process, and as will be seen later it appears to be negligible at pressure-reduction rates of less than 1·0 p.s.i. per month.

Saturation Pressure.

Beginning in 1931, when a successful bottom-hole sample taker had been designed, the saturation pressure of the crude had been measured in many wells. From these measurements it has been deduced that the saturation pressure in various parts of the reservoir before production began may have approximated to the values shown in Fig. 11.

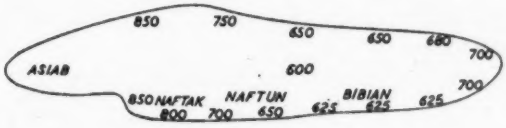


Fig. 11.

ESTIMATED SATURATION PRESSURES, P.S.I., BEFORE PRODUCTION BEGAN.

These values would apply only to the fissure system, and higher pressures undoubtedly existed in porous limestone remote from the fissure.

As far as is known, the Masjid-i-Sulaiman reservoir was full of oil when discovered, with no free gas in the crest of the structure. Seepages in the region of the crest were very active, and it is assumed that the liquid lost through seepage was made up by the rise of edge water, with the result that there was a slow loss of pressure throughout the reservoir. If there had not been any fall of pressure the saturation pressure of the crude would have been in equilibrium throughout the reservoir, that is, it would have increased with depth in the oil column only by an amount equal to the weight of a column of gas under the existing temperature and pressure conditions.

The slow loss of pressure, however, prevented this equilibrium being reached. The saturation pressure at the crest would be equal to the oil pressure, any free gas collecting there presumably escaping through the seepages almost immediately. Thus the saturation pressure at the crest would be decreasing with the oil pressure, and there would thus be a saturation-pressure gradient from all parts of the reservoir to this point. This gradient would cause a steady flow of gas by diffusion towards the crest, the length of path and its resistance to diffusion determining the saturation-pressure difference. Apparently the saturation pressures in the various parts of the field were all, or nearly all, less than the oil pressure at that point, and no free gas came into existence except at the very highest point of the reservoir, because diffusion took place faster than the pressure fell.

Mechanism of Oil Production.

A fairly clear picture of conditions in the Masjid-i-Sulaiman reservoir having now been built up, it was possible to visualize the mechanism by which oil was obtained from it.

When production first began, the crude was initially drawn from the fissures, which in turn drained the fissures in the crestal region, so forming a gas dome in which the pressure was lower than the crude-oil saturation pressure in the porous limestone there. As a result of this lower pressure in the gas-filled fissures, oil would begin slowly to ooze from the rock above gas–oil level. At the same time the loss of pressure in the oil zone occasioned by the replacement of oil by gas in the crest caused a zone or belt of reduced pressure to come into existence immediately below gas–oil level, the depth of this zone being equal in feet of oil to the difference between the saturation pressure at that point and the existing dome pressure. At the

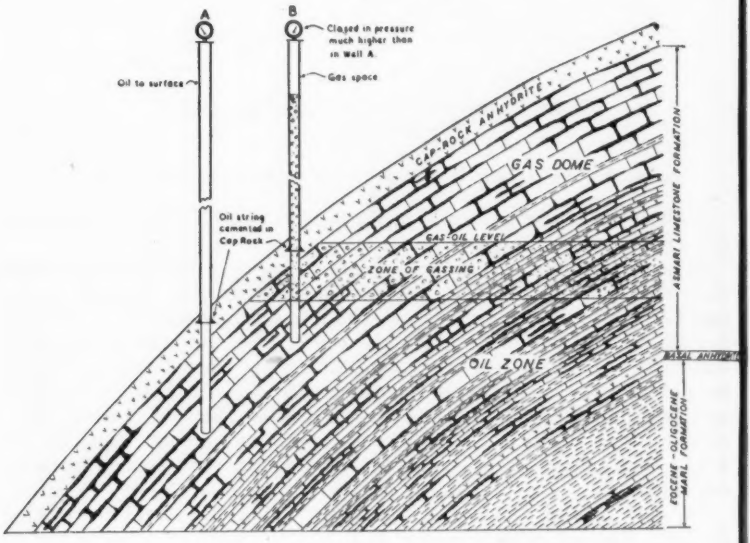


FIG. 12.

DIAGRAMMATIC CROSS-SECTION THROUGH RESERVOIR ON PRODUCTION.

lower limit of the zone the saturation pressure and the oil pressure were equal. This lower limit has been given the name of "saturation level." The result of this was that within this zone the oil pressure in the fissures was less than the saturation pressure in the adjacent porous limestone, so conditions existed for oil to be expelled from the porous limestone into the fissures.

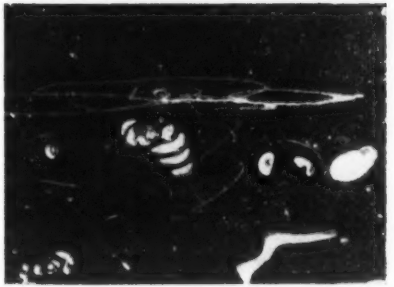
As the oil came out of the limestone it was accompanied by bubbles of gas which had been in solution in it, but as soon as they entered the fissure these bubbles migrated upwards to the gas dome. This explains why the fall of dome pressure is so very small. With the slow fall of dome pressure the belt of reduced pressure gradually became deeper (or thicker) and travelled slowly downwards with the gas–oil level. Throughout this zone, oil and gas are being expelled from the porous limestone and it is now

FIG. 1.

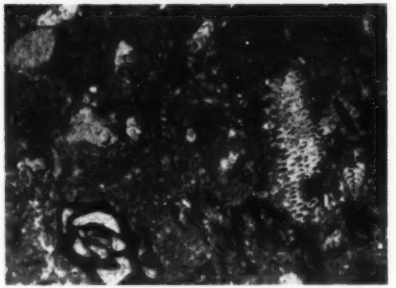
ASMARI MOUNTAIN.

[*To face p.* 388.

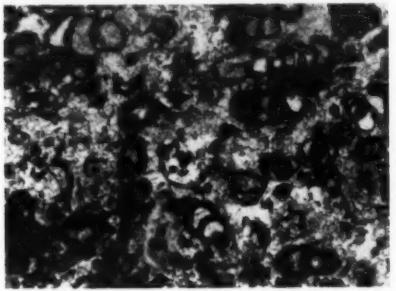
Type 1.
Porosity 2·0%.



Type 2.
Porosity 6·6%.



Type 3.
Porosity 12·5%.



Type 4.
Porosity 16·6%.

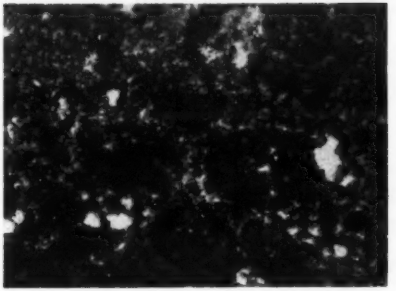


FIG. 9.

some 450 to 600 ft deep. At a rough estimate 15 per cent of the gas originally in solution in the oil remains in the reservoir and helps to maintain the dome pressure.

When a producing well is closed down, the casing fills with oil and registers a certain pressure at the well-head. On a number of occasions, however, wells, which have previously behaved in this way, suddenly began to fill with gas when closed in and registered a high well-head pressure. This change in behaviour is due to the fact that previously they were drawing oil from below the saturation level, but later the saturation level moved down past the bottom of the well and the bubbles of free gas coming

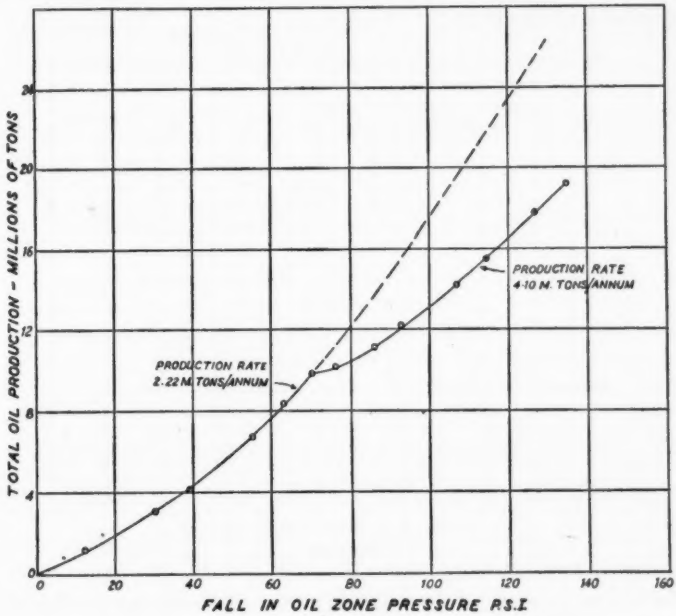


FIG. 9.

FIG. 13.

HAFT KEL. TOTAL OIL PRODUCTION AND FALL IN OIL ZONE PRESSURE.

out of the porous limestone with the expelled oil happened to be trapped by the well on their upward journey towards the gas dome.

By the time the re-examination of the reservoir rock had been completed and the experiment on the recovery of oil from porous limestone had been carried out, it had become apparent that far from being of negligible value in the production of crude, porous limestone was responsible for the greater part of the production obtained.

A final piece of evidence was provided by the Haft Kel field.

This field began producing in 1930, and by the early part of 1935 had settled down to a steady off-take rate of 2·22 million tons a year. Following the installation of new plant, the production rate was then increased

within the space of a month or so to 4·1 million tons a year. The resultant change in the rate of fall of pressure in the oil zone is very clearly defined, and it is interesting to note that several months, in fact more than a year, was required for the reservoir to settle down to the new rate. This does not look at all like drawing oil from a tank, for in that case the pressure–production curve should have continued along the same path at an accelerated rate. The pressure in the oil zone is the pressure in the fissure system as measured by observation wells. From this curve it is clear that the sudden increase in off-take was initially met from oil in the fissures, and this caused a sudden increase in the rate of fall of the pressure. This then acted as an increased differential pressure on the limestone, which responded very slowly.

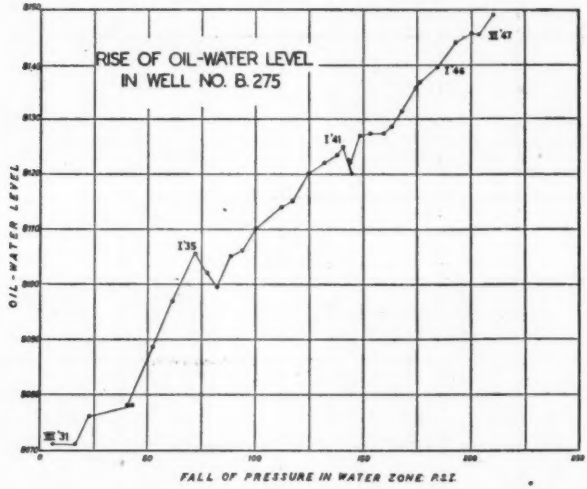


FIG. 14.

Surveying the whole of the evidence now available we can see that there is no firm dividing line between fissures and pore space. On high rates of production some of the finer fissures will behave as pores, while on low rates of production it is quite probable that the most permeable limestone will behave as fissures. It is possible to visualise a rate of production such that only a very limited quantity of oil has time to come from pore space, and from our experience of well No. 245 this rate is not as high as might be imagined. The point at which the open fissures begin to carry a disproportionate amount of the production load is quite sharply defined, and if it is exceeded it becomes almost impossible to control the reservoir, for, as will be shown later, edge water then begins to rise very rapidly.

After the incident of the sudden rise of edge water at Naftak in 1927, no serious difficulties were encountered in controlling the oil–water level for a number of years. Although at first it had been thought that the edge water was not rising, it was later found that there was a small rise

amounting to about one foot per month on the average. Some of the water observation wells in the Naftak area and on the northeast flank were sometimes very erratic in their movements but nothing serious happened.

It has already been stated that there must have been a flow of water into the reservoir to make up for the volume of oil lost by seepage, and the most likely place for it to come from would have been via the exposure at Asmari Mountain. The water-observation well nearest to the outcrop is No. B.275 and the record of the movement of oil–water level there, plotted against the pressure in the oil zone is given in Fig. 14.

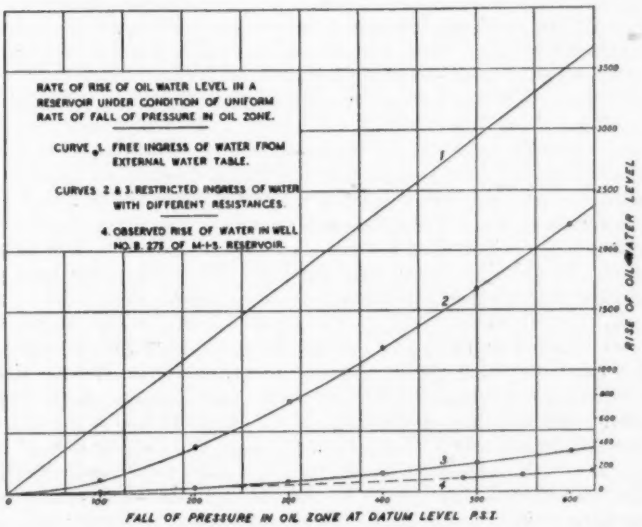

RATE OF RISE OF OIL WATER LEVEL IN A RESERVOIR UNDER CONDITION OF UNIFORM RATE OF FALL OF PRESSURE IN OIL ZONE.
CURVE 1. FREE INGRESS OF WATER FROM EXTERNAL WATER TABLE.
CURVES 2 & 3. RESTRICTED INGRESS OF WATER WITH DIFFERENT RESISTANCES.
4. OBSERVED RISE OF WATER IN WELL NO. B. 275 OF M-I-S. RESERVOIR.
1
2
3
4
RISE OF OIL WATER LEVEL
FALL OF PRESSURE IN OIL ZONE AT DATUM LEVEL P.S.I.

FIG. 15.

This record is, as far as can be seen, a straight line, and it is interesting to compare it with the rise of oil–water level that could take place under various conditions.

These different conditions are shown in Fig. 15. The first is the rise which would occur if there was free connexion to an external water table. This is a rapid straight line rise of nearly 6 ft for each 1 p.s.i. fall of pressure. The second is the rise which would occur if there was restricted connexion to an external water table; in this case the line is curved because the rise would be proportional to the steadily increasing differential pressure between the reservoir and the external source. The third is the rise due to a very restricted connexion to an external water table. In this case the

curvature is so slight that it is almost a straight line, and by comparison the rise of oil–water level in Well No. B.275 (No. 4) may quite well be due to a very restricted connexion to an external source.

A fact which must not be overlooked, however, is that a reservoir such as Masjid-i-Sulaiman contains an enormous volume of fluid in porous limestone below oil–water level, and that the reduction of pressure due to production, amounting to an average of about 15 p.s.i. per annum, is effective on this fluid. Although the compressibility of fluids is very small, when very large volumes are concerned the effect can be quite appreciable. It is now accepted that the rise of edge water in several oil-fields is due entirely to the decompression of water. It is probably safe to say that the slowly rising edge water at Masjid-i-Sulaiman is due to a combination of a very restricted connexion to an external source and to the expansion of the fluids in the limestone below oil–water level with reduction of pressure. The word fluids is used in this case instead of water, because in several wells which have drilled into the limestone below oil–water level, rock samples have been found to contain considerable quantities of oil in addition to water. The expansion of both oil and water over the range of pressures concerned is a straight-line effect.

In February 1937 a well on the northeast flank of the field which was then giving about 1000 tons of crude per day suddenly began to produce water. A short time before this occurred the off-take from the field had been suddenly increased from 11,000 tons to 16,000 tons per day. The result of the proportional increase in the sector concerned was that instead of the normal rate of fall of 1·5 p.s.i. per month in the oil pressure there, the fall was 3·75 p.s.i. in half a month, equivalent to a rate five times the normal. It was quite clear that the local rise of oil–water level to the producing well was due to the increased off-take which was initially supplied by oil from the fissures only. The rapid fall of the oil column in the fissures caused a similar fall of pressure on the fluids below oil–water level, which expanding under the reduction of pressure caused edge water to rise rapidly in the fissures. The question, which at once arose from this incident, was how a pressure drop of 3·75 p.s.i. in half a month caused edge water to rise 200 ft or so, when the same drop at the normal rate of 1·5 p.s.i./month would have caused the edge water to rise only 2·5 ft.

The reason would appear to be that at the normal slow rate of rise, the water has time to enter minute fissures and porous limestone and displace crude, and that when the rise is rapid there is no time for this to take place, and the water being confined to the small-volume fissure system has a greatly magnified effect.

The well which produced the water was shut in for four months and then re-opened to production, being then absolutely free from water, and the oil–water level had returned to its normal position.

This incident showed very clearly that a sudden increase in rate of fall of pressure at oil–water level must be avoided, and the rate of increase of off-take from Masjid-i-Sulaiman was therefore limited to 20 per cent in one month.

The displacement of crude from porous limestone by water has been examined experimentally. It was found that, as expected, a differential head was required to initiate the flow of water into oil-filled limestone,

the head depending upon the porosity of the sample under test. The quantity of oil displaced, however, seems to be more or less a constant proportion of the total oil in the limestone, amounting to something between 10 and 15 per cent. It would therefore seem to be less efficient than the recovery by dissolved-gas drive.

There also seems to be the risk that, if the fissures in which the water rises are widely spaced, large masses of limestone may be completely submerged before the displacement of oil is complete, unless the rate of water rise is very slow. On the other hand, if the limestone is well fissured,

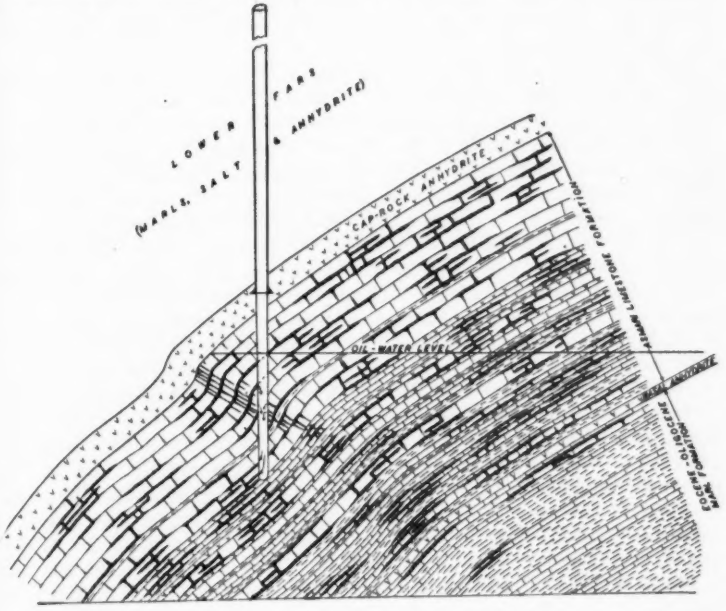


FIG. 16.

DIAGRAMMATIC CROSS-SECTION THROUGH PART OF RESERVOIR TO EXPLAIN DOWNWARD FLOW IN WATER ZONE AS IN WELL B.275.

complete blocks of it may be submerged before sufficient differential has been created to initiate the flow of water into the pores. Once a block of limestone is completely submerged by water there can be no further increase of differential, and therefore displacement of oil by water in production time is very unlikely. Samples of porous limestone obtained from well below oil–water level have always had a considerable oil content.

During the course of routine observation on the oil–water level in Well No. B.275, it was found that the temperature conditions were abnormal. It was ultimately discovered that edge water was flowing into the well through a fissure about 110 ft below oil–water level at the rate of 1000 gal/day, and out of the well through a fissure 155 ft lower down.

Fig. 16 is a very interesting illustration of what can happen in a reservoir.

Obviously the upper fissure belongs to a much more extensive system than the lower one, but the lower one is in contact with a considerable volume of porous limestone.

It is strange that in the most fractured part of the reservoir there should be an interval of 155 ft between fissures, and that these fissures are apparently not connected to each other except possibly at a higher level. Throughout the Bibian sector the average distance drilled into the limestone by the producing wells before obtaining satisfactory production was 70 ft, and there are indications that the distances between fissures increase with depth. The occurrence of fissures appears to be completely fortuitous; several attempts have been made to correlate them, but without the slightest success.

Although it has now become quite clear that porous limestone is responsible for the greater part of the production and that the quantity obtained from fissure space amounts probably to something of the order of 10 per cent only, the importance of the fissures must not be minimized, because without them production would be impossible. The Bibian sector of Masjid-i-Sulaiman is far more fissured than any other part of the field, and its productivity is greater than any other, that is, within the time and at the rate that oil has been produced from the field. The oil in the limestone at Bibian has a shorter distance to travel to a fissure, and therefore it comes out more quickly. In the less-fractured sectors of the northeast flank it takes longer, and therefore these sectors are much more sensitive to increases in the rate of production, because the porous limestone does not react so quickly as it does in Bibian. In Bibian the ratio of pore space to fissures is less than on the northeast flank. The production allocation to sectors is based on what they produce under steady conditions; if it were based on pore space the Bibian allocation would be less and the northeast flank more; if it were based on fissures Bibian would be more and the northeast flank less. During an increase in the production rate the allocation should be based more on fissures, since the initial increase has to be carried by the stock in fissures, and therefore a greater amount drawn from Bibian and less from the northeast flank. This is exactly what has been found in practice. Although the rate of increased off-take from the whole field has been limited since 1937 to 20 per cent in one month it was found better to draw most of this in the first place from Bibian and then slowly transfer the correct proportion to the northeast flank as the field steadied down to the new conditions. The reverse arrangement is required on reduction of throughputs, but as there are no ill-effects attached to a reduction no such action is taken. It is noticeable, however, that on these occasions the northeast flank sectors build up their gas–oil level more rapidly than does Bibian.

During the war it became necessary, owing to shortage of pipe, to shut down some of the production sectors on the northeast flank for a few years, and the uniform-pressure system of control established after the rise of water at Naftak in 1927 was no longer maintained. The pressure on the northeast flank was for some time about 25 p.s.i. higher than on the southwest flank. At one time this would have been regarded as a rather risky proceeding, but experience over the intervening years had shown that it was not the out-of-balance pressure which caused the trouble, but a high

rate of pressure change which was dangerous. There is no real need therefore to maintain a uniform pressure and uniform gas–oil level over the whole field, but doing so has the advantage that it makes rate of change of pressure easier to control, and, by preventing migration of oil from one sector to another, allows the relative productivity of the various sectors of the reservoir to be measured and so is of great help when estimating reserves.

Consideration of the rate of pressure change permissible in a field brings up the question of the optimum and maximum rates of production. Referring to Fig. 13 it would appear that at Haft Kel producing at 2·22 million tons a year was more efficient than producing at 4·1 million tons, because if production had continued at the lower rate it seems fairly certain that an additional 6·5 million tons of oil could have been obtained from the same pressure drop that gave a total of 16·5 million tons at the higher rate. Part of this 6·5 million tons would belong to porous limestone left behind by the more rapidly falling gas–oil level at the higher rate of production, and would undoubtedly be produced in course of time; it could therefore be regarded as deferred production. The remainder, being production from oil–water level, would be more likely to be lost, because if an appreciable part of the water rise was due to decompression, the rise would be more rapid and there would be less time available for this additional amount of water to displace crude in porous limestone, and so some crude might be lost.

At high rates of production it appears that the rate of reduction of pressure on the edge water causes the latter to rise at such a rate that it hardly has time to enter porous limestone at all, and one gets the impression of a rather unstable condition. If sudden increases in off-take are made with a reservoir in this state there are almost certain to be sudden and erratic rises of edge water. This condition was experienced at Haft Kel during the war when off-take from that field was at its maximum.

The maximum rate of reduction of pressure that a field will stand is dependent entirely on the degree of connexion to an external source of water supply and to the total amount of fluid below oil–water level subject to the reduction of pressure, both items being considered in relation to the nature of the fissure system, which, if small, is not in contact with sufficient oil-filled porous limestone to accommodate the rising water within a reasonable time.

Assuming that oil left behind above gas–oil level is deferred production and will eventually be obtained, the optimum and maximum rates of production for a field depend upon the rate of rise of edge water. If the rate of rise of edge water is fairly slow and uniform (such as the rate of 1 ft per month at Masjid-i-Sulaiman) and there are no sudden erratic movements, then the rate will not be far removed from the optimum. If, on the contrary, edge-water movements are erratic but are not subject to a general rapid rate of rise, it can be assumed that it would not be safe to increase the off-take beyond that amount.

For two reservoirs having approximately the same amount of recoverable reserves and the same edge-water conditions, but the one having a deep oil column and covering a smaller area, and the other having a shorter oil column and covering a larger area, the latter would be able to produce at

the higher rate, because for a given production the reduction in height of oil column would be less, with a correspondingly smaller rate of reduction of pressure on the edge water.

Provided the rate of production is such that the oil–water level rises at a reasonable rate the only other limitation is the permeability of the limestone. Experience at Masjid-i-Sulaiman suggested some years ago, but without any real evidence to support it, that the off-take from the field should not exceed 5 per cent per annum of the remaining recoverable crude in the reservoir. This seems to have worked very well, but the great difficulty in applying it is the estimation of the remaining reserves. The slower the rate of production the greater seem the reserves, as Fig. 13 indicates, and vice versa.

To adhere precisely to such a rule is not economic, because it involves building up to a peak rate and then almost immediately beginning to reduce. In actual practice the field would be brought up to 3 or 4 per cent of its estimated ultimate yield and then maintained at this steady rate for ten years or so until the rate is equal to 5 per cent of the remaining recoverable crude.

In describing conditions in the Masjid-i-Sulaiman field in 1927 it was stated that the value of gas conservation was fully appreciated and that the pressure in the gas dome was falling less than 2 p.s.i. per annum; it was later explained that the dome pressure was maintained with gas which had been expelled, together with oil, from porous limestone. For this oil and gas to come out of the porous limestone it was essential that the pressure in the fissure system should be lower than the saturation pressure of the oil in the rock, and yet the gas which collected in the dome and maintained the pressure there was also maintaining a similar pressure throughout the fissure system. The maintenance of the dome pressure is therefore preventing oil and gas from coming out of the porous limestone into the fissures. Instead of being allowed to collect in the dome and thus hinder the production of oil the gas should be produced with the oil to which it belongs. The gas–oil ratio of the crude coming from porous limestone is approximately 45 to 1, and the average gas–oil ratio of the crude arriving at the surface at the present time is about 35 to 1. The other 10 volumes are collecting in the gas dome. It is not physically possible to produce the whole of the gas which belongs to the crude with the crude, but that is not necessary, for all that has to be done is to produce sufficient gas from the dome to bring the overall producing gas–oil ratio up to 45 to 1. It is estimated that during the producing life of Masjid-i-Sulaiman about 15 per cent of the gas originally in solution in the crude produced from porous limestone has been collected in the gas dome.

Within the last thirty years considerable progress has been made in the improvement of the recovery of oil from sand reservoirs. Three different mechanisms are now generally recognized :—

(1) Water drive;
(2) Gas cap drive;
(3) Dissolved gas drive.

They are here given in the order of their efficiency. Both water drive and gas cap drive require a sand of high uniform permeability to reach

their greatest efficiency, and even then the rate of production must be restricted to something like 3 or 4 per cent of the estimated ultimate recovery, otherwise by-passing and channelling take place with consequent non-recovery of oil.

It is clear that neither of these mechanisms would be very efficient in the limestone reservoirs of Southwestern Iran with their enormous range of permeability, the range being from the infinite permeability of the fissures to that of the lowest porosity limestone. Although experiment has shown that some 10 to 15 per cent of oil in place can be recovered by displacement with water, the fortuitous nature of the fissuring would almost certainly prevent even this small recovery being effective over all the limestone submerged by rising edge water.

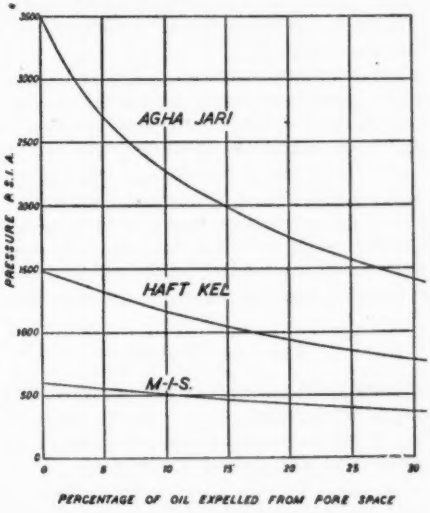


FIG. 17.

CALCULATED EXPULSION OF OIL FROM POROUS LIMESTONE WITH FALL OF PRESSURE.

It is also clear from the effect of gas accumulation in the gas dome described above, that the injection of gas to apply gas-cap drive to these limestone fields would not only be of no assistance, but would definitely reduce the amount of oil obtained, because it would put a back pressure on to the limestone surfaces of the fissure system.

It will be recognized that the production mechanism of Masjid-i-Sulaiman is mainly dissolved-gas drive, with gravitational drainage from the fissures at gas-oil level and water drive in the fissures and porous limestone at oil–water level as subsidiaries.

What will happen in the future in the fields of Southwestern Iran it is impossible to say, as none of the reservoirs there has as yet approached the end of its producing life, and we have therefore nothing to guide us.

The efficiency of dissolved gas drive in sand fields never exceeds about

25 per cent recovery of oil in place, the more usual recovery being 15 to 20 per cent as in the experiments of Fig. 10. In the sand fields, however, the rate of reduction of pressure has invariably been far higher than the rates in the fields of Southwestern Iran and it may be that in the latter the recovery may exceed 25 per cent.

The conditions limiting recovery is that when gas bubbles in the pores of the limestone link up and form a continuous gaseous path along which all gas subsequently evolved from solution passes to an open fissure without pushing any oil ahead of it.

It was mentioned previously that the saturation pressure inside a mass of limestone (and therefore remote from an open fissure) might be appreciably higher than in the neighbouring fissures. If this should be the case, reduction in pressure would cause bubbles to be formed first of all at the point of highest saturation pressure inside the limestone and thus give a higher efficiency of recovery.

In order to achieve maximum recovery a greater reduction of pressure is required in the higher pressure reservoirs as shown in Fig. 17.

In conclusion, it must be emphasized that no two oilfields are ever exactly alike. In these limestone fields the amount and variation of fissuring, the arrangement and occurrence of the various types of limestone, the edge-water conditions, and the saturation pressures of the crude, all affect the production mechanism and recovery of oil. An adequate number of observation wells by which the gas, oil, and water pressures and levels can be recorded is essential for the efficient control of the field, and to enable unforeseen occurrences to be quickly diagnosed and dealt with.

Vote of Thanks.

Mr C. A. P. Southwell (Member of Council), proposing the hearty thanks of the meeting and of the Institute to Mr Gibson for his lecture, said : It is a great privilege to me to be called upon to propose our thanks to Mr Gibson for his instructive and informative address.

It is unusual for a production engineer to reach the eminence which Mr Gibson has reached in scientific circles. The reason for that, of course, is that production engineers are to be found carrying out their work, which is often of a confidential or semi-confidential nature, in difficult climates far removed from scientific centres.

The brilliant exposition of the problem given by Mr Gibson to-night leads me to say that we would particularly wish also to thank the Council Committee which was responsible for getting Mr Gibson here. He is an investigator and research worker. A man of science who has spent the whole of his life in our industry in foreign fields. One who has played a great part in that amazing story of scientific development and reservoir research on an immense scale connected with the limestone reservoirs of the Middle East.

Mr Gibson has struck a new note so far as our Institute is concerned. He has flown here to deliver his lecture. I believe this is the first occasion on which the Institute can record having a scientist from foreign fields fly all the way back to this country to deliver a lecture and return to his job within a matter of days. Again the Institute is to be congratulated.

In the ceremony that is to follow, Mr Gibson is to receive the Redwood Medal for 1948. It is unusual for a petroleum engineer to reach that eminence; that is usually the lot of his colleagues on the geological or chemical side, but it is quite obvious from what we have heard to-night that this large-scale problem on which Mr Gibson has been working throughout the whole of his working lifetime is a scientific problem of a high order.

The lecture is particularly interesting and valuable to us because it will focus a lot of light on a large number of men who bear the heat of the day on the production and petroleum-engineering side of the industry, but who, owing to their living abroad for many years, are not often seen or heard by the Institute.

It is of the greatest importance to Britain at the present time that young Britishers should be ready to take up the Gibson baton when it is put down by Mr Gibson. In this sphere there is a great shortage of young men to man the scientific side of oilfield development and crude-oil production, particularly as to-day we are on the threshold of new problems connected with what we call secondary recovery from oil reservoirs. Such young men have not been trained during the war and, therefore, any stimulus which can be brought to bear at this time will be of extreme value, not only to the petroleum industry, but to the British cause.

Mr Gibson's work has been bound up, of course, with scientific unit development and conservation, so that water-free oil can be produced and the maximum flowing advantage obtained from conserving the dissolved gases. He has been dealing scientifically with reservoirs of such colossal size that it is difficult for those not associated with them to appreciate the magnitude of the problems involved.

After graduating in mechanical science at Cambridge in 1921, Mr Gibson went to South Iran in 1922 and was posted as a junior production engineer at the Masjid-i-Sulaiman field, which at that time was the only oilfield that had been discovered in the Middle East. The production was then at the rate of two million tons per annum, drawn from only fifteen wells, and very little was known about the reservoir from which the production was being taken. It had been established, however, that uniform pressure conditions extended in wells over a distance of five miles, and that the producing horizon was an Asmari limestone which outcropped in a mountain some 25 miles away to the south. Those few wells had either penetrated only a few feet into this limestone or obtained production in the caprock. The surface-production system consisted in flowing the oil by natural flow through pipeline to tankage, where the whole of the gas was flashed off to atmospheric pressure. From this tankage the oil gravitated to the first main-line pumping station. It is a remarkable tribute that 25 years later, a result of the work of Mr Gibson, of his Directors, and of his associates, the production is still water-free and by natural flow from this oilfield.

Thus Mr Gibson was fortunate in arriving in the Middle East at the time when the crude resources of that area were coming into sight. By arriving in the Masjid-i-Sulaiman oilfield in 1922 he came in at the start of those great developments which have so far brought the Middle East oilfield production from 2 to over 30 million tons per annum, a figure which will no doubt double or even treble.

Mr Gibson's work lay in two directions; first, the elucidation of under-

ground-reservoir conditions, or grand-scale hydrostatics, and secondly, the development of surface-production equipment to meet the conditions of development resulting from the first.

The story this evening is of the former, and I should like you to know of the great originality with which he approached the subject. There is not universal agreement with all his theories, but they are all most stimulating, and those that have so far been proved in practice have been attended by great success where methods of control have been applied under his guidance in the producing fields in Iran and also elsewhere where his advice has been sought.

Mr Gibson's close study and interpretation of the movements of oil and water in the large oil reservoirs with which he has dealt has contributed in no small measure to the scientific and sound early development of oil in the Middle East.

With regard to his investigations and researches into surface equipment, the high flowing pressures of the Haft Kel wells first suggested to Mr Gibson the possibility of multi-stage stabilization of the crude in such a way that the light ends utilizable in the refinery were retained. He devised multi-stage separators of the horizontal type of a very high efficiency, and thus obviated the use of gasoline-recovery plants, together with the attendant power and water supplies, the provision of which is so difficult in undeveloped areas.

It is of interest to us that Mr Gibson, despite being so far away, has been directly or indirectly associated with a number of our Presidents who have taken the greatest interest in our Institute. That direct or indirect association starts with Lord Greenway, continues with Lord Cadman, Sir Thomas Holland, and Mr T. Dewhurst, who is here to-night. Then there was Sir William Fraser, the Chairman of the Anglo-Iranian Oil Company to-day, and Mr J. A. Jameson, the Director of Production, who directed the work which Mr Gibson carried out. They have seen that scientists such as Mr Gibson have been able to develop their ideas.

It is good news to hear that Mr Gibson is shortly taking up residence in England; and I hope that the young men of the Institute, particularly, will have the opportunity of hearing more from him then. It would be of great value to the Institute that that should be so.

In thanking him for his fine exposition this evening, I should like on behalf of the Institute to wish Mr Gibson many more years as an elder statesman of scientific petroleum engineers, so that we may have the benefit of his presence in the future.

I would invite you all to thank him for his excellent Address and for having travelled to this country in order to deliver it.

(The vote of thanks was heartily accorded, and the applause was prolonged.)

Presentation of the Redwood Medal for 1948.

The President, Sir Andrew Agnew, C.B.E., presenting the Redwood Medal to Mr H. S. Gibson, C.B.E., said: The lecture we have heard this evening shows clearly that in Mr Gibson we have a man of very sound knowledge, a progressive thinker and a man of action, having the ability

and courage to give effect to his ideas. The reformatory projects he has introduced according to a carefully preconceived pattern, and his brilliant leadership, have had a great appeal throughout the whole petroleum world.

I distinctly remember hearing, in the early days, of what had been done in the limestone fields in Persia; and this evening it has been brought very vividly to my attention that probably the man who has had more to do with it than most is Mr Gibson. Bearing that in mind, it makes me feel that the selection that has been made by the Council for the honour which it is my privilege to bestow on Mr Gibson has been very proper. (Hear! Hear!)

Before presenting the Redwood Medal to Mr Gibson, however, I must remind you that this Medal commemorates a very courteous English gentleman who devoted his whole life to the study of petroleum. Sir Boverton Redwood was born on April 26, 1846, in London; so that this evening we can say that we are celebrating the one hundred and second anniversary of his birthday. In 1869 he was appointed Secretary to the Petroleum Association, just ten years after Drake struck oil in Pennsylvania. Therefore, he could legitimately be classed with the pioneers of the petroleum industry. His earliest work was in connexion with the testing of the flash point of mineral oils. In 1872 he gave evidence on the subject before a Select Committee of the House of Lords. His evidence was again called for by a Select Committee of the House of Lords in 1883. In the same year he made an exhaustive inspection of the petroleum industry in the British Isles and the principal countries of Europe.

Three years later the Redwood viscometer was accepted as a standard by the British Government and the trade. The apparatus which he designed to detect the presence of petroleum vapour has been in use since 1894. Other pieces of apparatus are also associated with his name.

Late in the last century he took an active interest in the internal-combustion engine. The first four-cylinder Daimler car was constructed to his order and exhibited to the Prince of Wales, afterwards Edward VII. Later he served on Lord Fisher's Royal Commission on Fuel and Engines, and became Chairman of the Gas Tractor Committee in 1917.

For his many services he was Knighted in 1905, and received a Baronetcy in 1911.

The very active part he took in the foundation of the Institute of Petroleum, and the very high appreciation in which he was held, are well reflected in the fact that he was our first President. He died in 1919.

It is the spirit of this brilliant and progressive leader which is symbolized in the Redwood Medal, the first and for a time the only Medal of the Institute.

And now, Mr Gibson, for your fine talent and continuous service to the advancement of petroleum, it gives me great pleasure indeed to present to you the Redwood Medal.

(The Medal was presented, amid prolonged applause.)

Mr Gibson, responding, said: Mr President, ladies, and gentlemen: I feel very greatly honoured to receive the Redwood Medal. It is one that I shall treasure throughout the whole of my life; it will always be an

inspiration to me. I hope, as Mr Southwell has hoped, that we can train more production engineers in the years to come.

I thank you all very much.

MR G. H. COXON: May I propose, on behalf of the Council, a vote of thanks to the Directors of the Anglo-Iranian Oil Company for having made it possible for Mr Gibson to come here. It is not easy to arrange for such a man to be away from his job under present conditions, and his responsibilities must be carried by someone else.

THE PRESIDENT: I should like very much to have the privilege of seconding the vote of thanks, and I am sure it will receive the recognition it deserves, which is very great indeed.

(The vote of thanks was accorded with acclamation, and the meeting closed.)

Sir Andrew Agnew, C.B.E.

President 1946–1948.

[*To face p.* 103.

THE U.K. PETROLEUM INDUSTRY IN WAR.*

By Sir Andrew Agnew, C.B.E. (President).†

Introduction.

Many of you have no doubt heard the expression, "The Impossible Done Now—Miracles Take Slightly Longer," in connexion with some outstanding feat of arms during the recent war. The origin of this expression is variously claimed by the 14th Army, the 8th Army—and even by a Churchman on the B.B.C. the other day. I do not propose to enter the lists of the claimants, but I can state as a fact that a notice to this effect was displayed in more than one Petroleum Board Depot as far back as the very early days of the war.

Even if the expression did not emanate from there, that it was so exhibited serves to focus attention on the magnitude of the task that the United Kingdom Petroleum Industry had to undertake. Let it never be forgotten that the task *was* as mighty as it was exacting. It is certain that the industry will never forget it. Modern, mechanized war is waged with oil, and the contestant who can rely on having abundant supplies at the right time in the right place will emerge the victor.

When the task was over, the expression to which I have just referred became charged with even greater significance. For, even if the "miracle" of our success was a miracle within a framework of logic and hard facts, it was nevertheless accomplished when many intelligent observers of the British situation during those anxious years believed that we had accepted an impossible task. In case I should be accused of extravagance in expression, may I add that the word "miracle" appears in my address in inverted commas.

In the sphere of aerial warfare, perhaps most of all, things were accomplished that few men believed to be possible, even when the conflict had been raging for some time. There were many notable doubters, as you will well remember, of the plans to send out mass heavy-bomber formations to raid Germany night after night. The idea, they believed, would not work: the fuelling problem in supply and distribution would, the critics contended, be too vast.

Their doubts were understandable, for the provision of aviation fuel on such a colossal scale had never before even been contemplated. At his most arrogant, Hitler did not conceive of raids on Britain involving bomb-loads much exceeding 400 tons. Yet in the mass air-attacks made by the Allies on the Reich during the later months of the war, bomb-loads of 4000–5000 tons were carried regularly to the target.

The magnitude of the fuelling problem at that time can be measured by the fact that the quantity of aviation fuel consumed by bomber and fighter

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* Presidential Address read at the 35th Annual General Meeting of the Institute of Petroleum on April 30, 1948.

† Chairman of the Petroleum Board.

aircraft operating from Britain was over seven times that envisaged by the experts in 1939 as the maximum likely to be required in war. A single big raid over Germany could mean the consumption of 3 million gallons of fuel, or a complete tanker cargo. Such raids often occurred twice in twenty-four hours at the peak of the campaign.

Approximately 94 per cent of Royal Air Force and United States Army Air Force aviation gallonage was delivered to airfields by Petroleum Board tank wagons. Success in this enormous task depended on attaining two objectives which were in themselves conflicting: the first objective was to maintain supplies to aerodromes sufficient to meet all fluctuating requirements; the second, to keep drivers and vehicles usefully employed between

THE EFFECT OF EFFORTS TO ATTAIN STILL FASTER LOADING AND DELIVERY AS SEEN BY DRIVER A. G. MIDGELEY.

periods of peak demand at individual points. Thanks to the alertness and ability of the Board's Regional Transport Officers, and to the excellent co-ordination between depot and aerodrome personnel, the Allied bombing fleets always had their fuel to time.

Thus, gentlemen, the impossible, in this respect, did become a fact. I propose to return to this aspect of our activities later in my address. Here, it is perhaps enough to note that the work of the Petroleum Board in the greatest of all our military tasks earned the unremitting praise of both British and American military and air-force leaders. That this task was accomplished, implies that all the minor problems, none the less difficult and arduous, were overcome too. They were; and this address is an account of how the organization of the Petroleum Board came into existence, and what it contributed to the winning of the war.

Conception of the Petroleum Board.

The organization to be known eventually as the Petroleum Board, was conceived during 1938, when events were leading up to the Munich crisis. Consultations with various Ministries and with the Services took place

during the summer, and the Petroleum Board actually came into existence, with Government approval, at the height of the Munich crisis. The Board was then only a planning instrument, a purely voluntary body to be kept in the background until a national emergency, such as the outbreak of war, should necessitate it becoming a functional part of the war effort. In our own way it can be fairly said that we were among the first of those gentlemen to become known as " the back room boys."

On the original Board there were representatives, at that stage, of the four leading distributing companies and their associates—Anglo-American Oil, National Benzole, Shell-Mex & B.P., and Trinidad Leaseholds. It was these men who were assigned the task of formulating a plan to handle oil products in war-time.

They began by creating specialist working groups to deal with individual aspects of the overall problem. These groups established liaison with the interested Ministries and, of course, the Services.

By January 1939 the work of the groups was correlated and combined in a document to become known as " Petroleum Distribution : Emergency Arrangements." The document was divided into seven reports, and with commendable conciseness arrived at conclusions on all the most important aspects of the oil industry in war-time. Some of the more notable subsections were : the pooling of man-power and physical resources; the expansion of the Board to include the smaller distributors in the plan; fire-fighting and A.R.P. arrangements; co-ordination of transport and driving staff; vehicle lighting in the prospective black-out; field operations; control and operating of rail tank cars; and vehicle-repair arrangements.

In addition to these operational needs, a complete new accountancy system, for the " pooled " products, had to be devised, and was included in the document. Other recommendations included drastic reductions in the number of grades of petroleum products normally necessary and used in peace-time.

One of the most interesting features of the original document is that it virtually remained the administrative operations book of the oil industry throughout the whole war, with hardly any major change. It is a claim which, I believe with all modesty, it is not possible to make for any other essential organization conceived in peace and applied in war.

In the eight months of 1939 that preceded the outbreak of war, organization in detail went on both in London and throughout the thirteen Petroleum Board Regions, most of which coincided approximately with the Regional Defence Areas. This was not, of course, merely paper planning. More than eleven hundred installations and depots were surveyed and classified into one of three categories : (1) operational, (2) in reserve, (3) to be closed for the duration. These decisions were freely taken without regard to any factor other than whether the installation was the best one for the particular war-time, as opposed to peace-time, requirement.

Legally, the Petroleum Board could have been the most difficult problem of the war, if too strict interpretation of a variety of matters had been written in the Board's organization. In reality, the original four companies committed themselves to the " pooling " arrangement by virtue of two simple agreements—one signed in September 1938, and the other in March

1939. In May 1940 the thirty-two independent companies, who had been part of the pool from the outbreak of war, signed the third agreement. Finally, the fifty-seven non-importing oil-distributing concerns were affiliated.

These documents also included, by agreement with His Majesty's Government, a section dealing with the dissolution of the Board and the return to normal company conditions after the end of the war.

By the outbreak of war, the whole organization had been planned to the last detail, and two days before the war was declared, every Regional Manager called together his District Operators and gave them the outline of the oil industry as it would function in war-time. Even the stationery and forms to be used by the still publicly non-existent Petroleum Board were then awaiting despatch to each District Operator's selected office, and all was ready by the fateful September 3. The Pool became effective at midnight on September 3–4, 1939. At that moment, the oil companies voluntarily surrendered for the duration of the war their operating independence, and their then staff of 20,000 became employees of the Petroleum Board.

In looking back, it was not the enemy but the British public that gave us our first crisis. In anticipation of motor-fuel rationing, people carried away petrol in every conceivable kind of container, and the Board was inundated with orders from garages. The District and Regional offices were soon knee deep in orders.

Once that crisis was over, however, the Board personnel began to knit themselves into a team in the finest possible spirit. They had one thing in common—a mutual regard for one another and for the oil industry.

The Board was the result of the voluntary combination of the leaders of the oil industry, still in charge of their own affairs, but fully mobilized for war and subject only to policy direction from the Government. Nothing contributed more towards the magnificent team spirit developed throughout all levels of the Petroleum Board than the knowledge that it was still a case of the oil industry doing the things which the industry was best qualified to do.

Organization of the Petroleum Board.

The success of the Petroleum Board was largely due in the first instance to meticulous organization by men who knew their industry, combined with a sensible degree of decentralization of responsibility that was worked out before the war began. In this way, the Board had the best possible start, and did not suffer from the simultaneous planning and operating troubles which other war-time organizations experienced. As to relations with the Government, while the Government naturally retained the powers of general direction, the Board was executive and its duties were defined quite simply as supplying, shipping, and distributing petroleum products. An important aspect of the Board's charter—if that word can be used—is that we were given sufficient freedom to operate on commercial lines as far as the emergencies of war would permit.

On the Government side, the Board's contacts were chiefly with the Petroleum Department of the Mines Department (which later became the

Petroleum Division of the Ministry of Fuel and Power), with the Ministry of War Transport, and with the various Service Departments.

At the highest level, policy on petroleum matters was vested in the Oil Control Board, which was a War Cabinet Executive. The Parliamentary Secretary for Petroleum presided over the Oil Control Board, thus creating a direct link between the War Cabinet and the department responsible for carrying out Cabinet policy. The Petroleum Board was represented on the Oil Control Board, as were also the Ministry of Fuel and Power, the Ministry of War Transport, and the Services. At a later date, the Oil Control Board included representatives of the American Government and Military members.

The Trade Control Committee was formed, consisting of the Petroleum Board Chairman and various Executive Directors. The functions of this Committee were to supervise and co-ordinate the work of the Petroleum Board in its widest aspects, and to serve as a channel for advising the Government on major matters affecting the industry as a whole.

As supplies and tanker tonnage required for the United Kingdom could not be treated as a self-contained matter, it was also found necessary to expand the Board's organization so as to dovetail its requirements into the general overseas programme. For this purpose, the Overseas Supply and Tanker Tonnage sections of the Petroleum Board were developed, to become central executive bodies for the entire British Petroleum industry, dealing with supply, programming, and the provision of tanker tonnage for the United Kingdom and for overseas territories.

The executive Departments of the Board numbered three, and were :

(1) Physical and Supplies.
(2) General Sales.
(3) Finance and Accounts.

The headquarters staff was a remarkably small part of the total organization, due to the best business practice of de-centralization of responsibility. Regional Managements were encouraged to exercise the greatest possible initiative, in both the administrative and operational spheres, so long as the overall Board policy was being implemented. This Regional autonomy exhibited itself in the differences in regional organization that existed throughout the country, each fashioned to a major degree by the ideas of the Regional Management. The Board never had cause to regret their original principle of " trusting the man on the spot." Mention must also, of course, be made of that important offshoot of the Petroleum Board, namely, the Lubricating Oil Pool. This was an importers' pool with twenty-one members, and worked as a separate entity.

The foregoing is an outline, in its essentials, of the structural organization of the Petroleum Board, as the war-time instrument of the oil industry.

Development of the Strategic Plan.

The strategic plan for petroleum was based on the assumption that the East Coast ports would cease to import supplies of oil. In formulating this plan, the Board demonstrated the realism and foresight which have characterized its activities throughout. From the outbreak of war, U-boats

and the Luftwaffe hampered coast-wise and canal movements in the East, and Norway's fall virtually closed the East Coast altogether. The measures already in hand by which oil imports could be switched to the south provided an invaluable breathing-space before the collapse of France, in May 1940, closed that coast also, and threw us back on our last resource, the West Coast.

If the Petroleum Board had not displayed exceptional vision in preparing its plans well before the outbreak of war, and equally exceptional energy in translating them into action, the Western ports could never have been developed and equipped in time to meet the desperate post-Dunkirk situation.

This drastic re-routing of supplies presented a tremendous problem in itself, for in peace-time 52 per cent of our oil was imported to the East Coast and another 10 per cent on the South Coast, leaving only 38 per cent as the normal quantity absorbed on the West.

The physical difficulties which had to be tackled were formidable in the extreme. Entire new tanker berths had to be constructed, and special facilities for shore steam installed to supplement ships' steam, so that ships' pumping equipment could be worked at maximum capacity. Many additional pipelines between tankers and terminal installations were also provided. At one port, for example, pipeline extensions enabled tankers at eight berths each to discharge simultaneously at the rate of 800 tons per hour. The effect of such improved facilities was to increase the average rate of all tanker discharge in the United Kingdom from 100 tons to no less than 450 tons per hour. From the early days, the urgent problem of co-ordination at ports to minimize tanker turn-round time had been ably handled by a special section of the Tanker Tonnage Committee, who were instrumental in the appointment of Port Superintendents abroad to co-operate in this most important side of the job.

As American participation in the European theatre of war gathered momentum; the Board further foresaw the necessity of equipping the Western ports in readiness to receive cargoes carried in the later war years by American tankers of much greater tonnage than any previously discharging at United Kingdom ports: by the time these vessels began to arrive, the expanded port facilities necessary for the handling of their cargoes were already installed. 16–18,000 ton vessels of this modern type discharged at rates sometimes exceeding 1200 tons per hour, and in the first eighteen months during which they were on regular service to Britain, they brought between 10 and 11 million tons of oil products, involving over 700 arrivals. It can be imagined what this meant in the calculations of the Allied High Command, planning for D-Day.

Overland distribution took on an entirely new aspect as a result of this complete dependence on West Coast intake. On the one hand, previously existing distributional schemes had become obsolete because of the elimination of some of the most important pre-war importing points. For instance, London, which in peace-time provided entry for 36 per cent of Britain's oil supplies and served a wide adjacent area, ceased to import any oil at all.

On the other hand, a number of areas which in pre-war days were relatively modest consumers of petroleum products became, for war reasons, centres of peak demand. A case which at once comes to mind is that of the

Eastern Region (East Anglia), much of which was transformed by war events from a thinly populated agricultural district to an armed camp on the grandest scale. It provided not only the main spring-board for the giant air offensives against Germany, but also one of the most concentrated assembly and training grounds for the American forces when these poured into Britain. The effort demanded in meeting the resultant calls for petroleum fuels and oil was therefore prodigious, as may be judged from the fact that, whereas the United Kingdom trade in motor spirit for 1938 totalled some 5 million tons, home deliveries of aviation spirit alone were in June 1944 running at a level exceeding 6 million tons annually, with the Eastern Region's share amounting to no less than 45 per cent.

Most of the storage capacity for this enormously increased offtake had to be specially constructed as the needs arose, and a great bulk of the aviation spirit supplied to this area had to be brought from the West by road. The strain on the Board's road-transport service, and indeed on every member of its staff in the Region, was therefore great and prolonged, yet at no time were air or military operations there held up for lack of fuel. Concurrently with this expansion in supplies to the Services, moreover, the requirements of kerosine for agricultural purposes were also rising very fast.

In coping with the new country-wide distribution problems as a whole, much was achieved by close co-operation with the railways, and out of this cordial partnership was born one of the outstanding war-time innovations in Britain—the complete oil-train. With port storage space severely limited, tankers arriving in rapid succession, and the need for speedy turn-round paramount, it was essential to operate inland-distribution vehicles in fleets of a size capable of dispersing complete cargoes as they arrived. Instead of using the Board's fleet or railcars, which by 1944 numbered 10,000, in haphazard and piecemeal fashion, complete railcar trains were assembled, functioning as single units from starting point to destination. This expedient not only secured an immense saving in turn-round time at the ports, but greatly facilitated control, flexibility, and continuous movement in overland distribution. 15,000 of these bulk trains were loaded in 1944 alone. They averaged 250 to 400 tons in capacity, and by their use it was found possible to double the pre-war tonnage of oil products transported by rail.

Another example of the Board's resourcefulness was the creation of special railheads, serving as local oil distribution centres. The first of these was opened to feed West London, and was an emergency measure imposed by the "blitz," but in this case, again, plans were already scheduled.

In 1941, in anticipation of the enormous expansion in oil supplies which the growing war-effort would entail, work was started on the construction by the Board on behalf of the Government, of an elaborate pipeline system provided with numerous secret specially protected underground storage tanks capable of holding large reserve stocks with the maximum of safety. By the end of 1944, this system was a thousand miles long, and thousands of millions of gallons of oil, including hundreds of millions of gallons of high-grade aviation spirit, had passed through the pipelines. Without them, the build-up of the Allied military strength to anything approaching the desired scale would have been impossible: the ultimate and overwhelming

ferocity of the massed air attacks from Britain would never have been reached, and the problem of satisfying the huge petrol needs of the Armies of Liberation would have been virtually insoluble.

As invasion threatened Britain in 1941, it might have been excusable if the scheme had not been put into operation. But it was. The work went on patiently month after month, often in the face of immense physical difficulties. It was with pardonable pride that the industry saw every section of the line completed to time, and in many instances, before schedule. The full worth of the pipelines was to be proved later, when, in 1944, some 4½ million tons of petroleum products moved through the system. That, in theory, meant the saving of 4½ million tons of railway and road transport; in actual fact, such additional road and rail transport was simply not available.

In time, the pipeline system was extended under the Channel, and then across France, Belgium and Holland. This meant that our Armies advanced across the Continent using fuel that reached this country on the West Coast, whence it was pumped through Britain, under the ocean and as far as the German frontier.

With all that could be done by other methods, however, the main burden of coping with the transport problem fell upon the Board's own road-transport service which responded nobly. The 5000 road vehicles which it controlled at the outbreak of war remained practically unaltered in number throughout, although as time went on the proportion of tank wagons exceeding 2000 gallons in capacity increased from 6 per cent to 20 per cent of the total. The additional road transport required was therefore secured mainly by two means—doubled- or trebled-shift working of the available vehicles, and more intensive and economical use of drivers. The larger spirit vehicles averaged some 5000 miles monthly, and the smaller vehicles, operating in a more limited area averaged 1200 to 2000 miles monthly.

Herein lay a specifically human problem, apart from the material difficulties so far discussed. As with the vehicles, the supply of drivers remained fairly steady at just over 5000 until, towards D-Day, it became imperative to recruit a further 1000 reserve drivers. With so limited a labour force, it was only by planning and organization of the highest order that the myriad and diverse needs of the Services were met. Fuel supplies had to be kept moving with the utmost rapidity and smoothness, which entailed extreme mobility on the part of the drivers. Out of a total strength, in 1945, of 6250 drivers, 4000 worked away from home for periods varying from weeks to months, and some 3000 were permanently "on transfer." Their unstinting efforts and loyalty under such trying conditions proved not only their own high quality as employees, but also the excellent relationship throughout between these men and the management. The drivers worked long hours uncomplainingly. At the time of the Normandy landing, they were on the road for anything up to sixty-four hours a week.

Nor should mention be omitted of the sterling work done by the thirty-three motor repair shops and the field maintenance staffs, without whose efficiency and energy the vehicle fleets could never have stood up to their punishing task.

The success with which the whole undertaking was carried through was as much as anything due to the Board's express policy of delegating, as far

as possible, full responsibilities and powers to "the men on the spot," and the avoidance of anything savouring of bureaucratic obstruction at the centre.

Save for one brief period after the 1940 debacle, when a glut of fugitive tankers clogged our ports, the progressive shortage of tanker tonnage presented an equally acute problem in oil logistics. At the time referred to, some of these temporarily surplus tankers actually had to be ordered back to loading ports, or dispersed to remote waiting points, but they were absorbed into the normal carrying trade as the war went on, and the huge expansion of demand, coupled with the crippling losses suffered by the tanker fleets, created a state of chronic tanker shortage. No less that 219 deep-sea tankers sailing under the British flag, totalling some 2¼ million D/W tons, were destroyed by enemy action between September 1939 and May 1945; this was equivalent to 54 per cent of the fleet at the outbreak of war.

It took great ingenuity and not a little diplomacy to get American tanker help in the days before Lend-Lease, for no American vessel was allowed in belligerent waters. To mention only one achievement out of many, the Board succeeded in chartering American tankers to carry pertroleum from the West Indies to the Atlantic seaboard, at which point the hard-pressed British tanker fleet took over for the trans-Atlantic haul. By this arrangement the ocean haul navigated by British tonnage was shortened by 1000 miles, which in time of war, meant a saving of anything up to a month in sailing time, depending on convoying conditions.

The Shadow of Invasion.

With the British Army back from Dunkirk, and the Continent alive with German troops, 1940 was essentially a year of defensive measures. Apart from the sheer struggle for survival along the sea lanes, there came the period of the heavy air bombardment of Britain during which petroleum installations were key targets. Here, one must pay deserved tribute to the heroism and devotion to duty of the men who fought the incendiary bombs, and preserved again and again precious oil supplies at the risk of their own lives. The impressive list of awards for bravery is evidence enough of the spirit in which this phase of the battle for oil was fought out.

But even while these threats to our supplies were causing us serious concern, the Government asked us to devise a plan whereby supplies in the Eastern part of the country could be denied to the enemy should he land on British soil.

This became known as the "Pink Area" scheme, because the area in which these denial measures were necessary was marked in pink on the strategic maps. The problem presented to us by the Services was to prepare a simple yet effective method of immobilizing oil supplies in that region. The Board had 26,000 motor-spirit customers in the Pink Area, but though the Government closed down the great majority of these establishments, we were left to deal with nearly 5000 pump sites. These had to be prepared for immobilization—and that was no small task. But, in addition, the closing down of some 21,000 retail establishments and commercial pump sites meant that the Petroleum Board had to uplift all stocks from the closed sites.

Coupled with the forced reduction of our own storage in the Pink Area, this task resulted in our transport being on duty for eighteen and often more hours a day.

Yet, this was at the time of the Battle of Britain, and never once throughout the war was an aircraft operating from the United Kingdom grounded because of lack of fuel.

Speaking of the Pink Area reminds me that "de-pinking," which began on November 1, 1944—during the heightening attacks on Germany—was no mean feat when our organization was being stretched to the utmost to maintain the offensive.

In general retrospect, I feel it is important to put on record that, over and above the immense task of providing and distributing oil supplies in an unfailing stream, a great deal of time was spent by the Petroleum Board doing things which fortunately were not eventually needed. This was especially true in respect of purely defensive measures, as, for example, preventing the enemy being able to use the installations in the event of a successful landing in Britain.

From Defence to Attack.

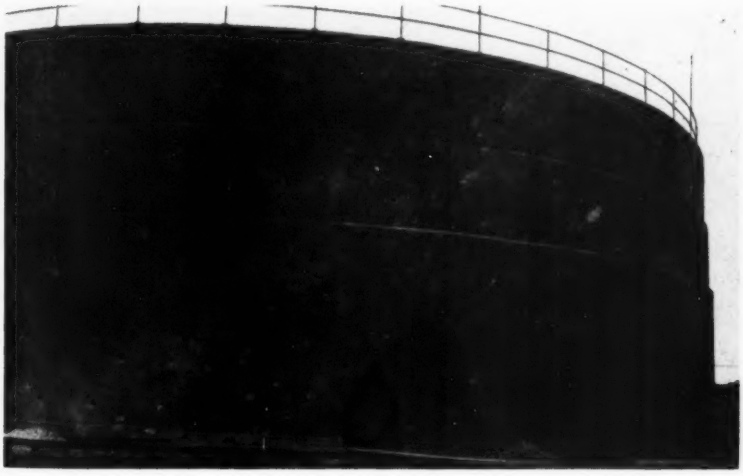
There was, however, the great compensation of intense constructive activity as well, as Britain and her Allies moved decisively from defence to attack. There was a ceaseless battle of wits between ourselves and the enemy over petroleum. For our part, we depended on our Technical Advisory Committee which in turn fathered other intelligence and scientific groups to study German fuel supplies, plant, equipment, and the quality of fuel used.

Then, the Petroleum Warfare Department was organized by the Parliamentary Secretary for Petroleum, and the Board entered with zest and vigour into a new sphere in which petroleum assumed many novel roles. This lively Department became responsible, as you heard in a previous address, for the design and perfection of flamethrowers of many types, including the Churchill Crocodile tanks which led the assault on D-Day. Among its outstanding achievements were PLUTO—the pipeline under the ocean, and FIDO—the device for dispersing fog on airfields which saved the lives of thousands of Allied pilots and at the same time enabled the British and Allied air forces to take the offensive when the German air force was grounded. The Petroleum Warfare Department had at its disposal the wealth of technical resources—and the men equipped to use them—on which the oil industry has always prided itself, and which contributed substantially to the success of this aspect of scientific warfare.

In this phase of the struggle, to meet the needs of the vast expansion both of our own and of the American forces pouring into the country, Britain was turned almost literally into an immense oil dump. It was not only a question of overcoming the hazards of bringing petroleum into Britain from overseas in quantities never previously approached or even contemplated. Once it arrived the oil had to be discharged without delay, distributed forthwith, and stored.

Time does not permit me to deal at length with the many less spectacular but no less solid achievements of the oil industry. Some of them which

THE 1940 BLITZ TOOK HEAVY TOLL OF PETROLEUM INSTALLATIONS. THE RESULT OF A HIT ON A THAMES-SIDE INSTALLATION IS SEEN ABOVE.



BLAST WALLS WERE VERY EFFECTIVE IN PREVENTING BOMB FRAGMENTS FROM RUPTURING THE TANK.

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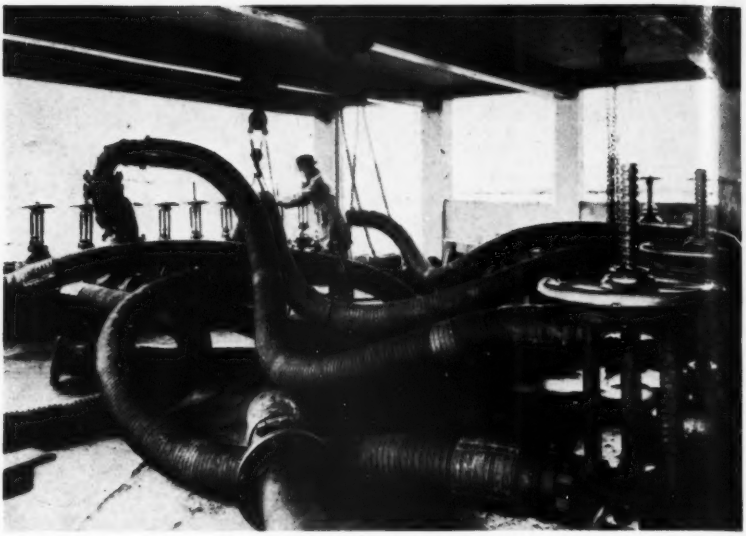
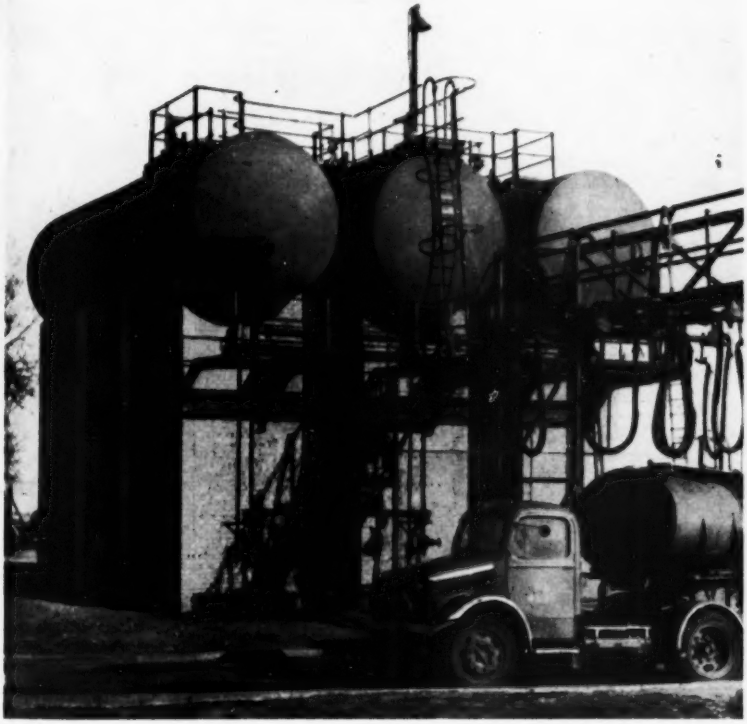


A STRIKING IMPRESSION BY MAURICE BECK OF THE EXCHANGE PIT AT ONE OF THE AIR MINISTRY'S AVIATION-FUEL DISTRIBUTING DEPOTS RUN FOR THE GOVERNMENT BY THE PETROLEUM BOARD TO SERVE R.A.F. AND U.S.A.A.F. AIRFIELDS.

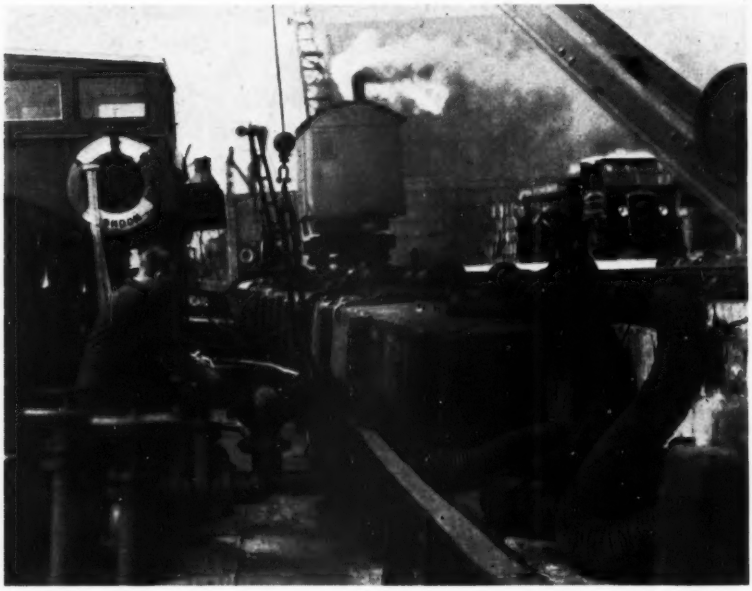
ARRANGEMENTS WERE MADE AND COMPLETE INSTRUCTIONS ISSUED FOR THE IMMOBILIZATION OF KERBSIDE PUMPS SHOULD THE NEED ARISE.

A 1942 ADDITION TO THE PETROLEUM BOARD'S ROAD FLEET—A SCAMMEL ARTICULATED 3600-GALLON SIX-COMPARTMENT SPIRIT TANKER.



ALTHOUGH THE TOTAL STORAGE CAPACITY AT THIS BUSY "BLEED POINT" ON THE AVIATION CIRCUIT OF THE U.K. PIPELINE WAS ONLY 36,000 GALLONS, ITS ROAD FLEET DELIVERED AN AVERAGE OF 175,000 GALLONS DAILY TO BOMBER AERODROMES WHEN ALLIED AIR ATTACKS WERE AT THEIR HEIGHT.

THE SUCCESS OF THE EFFORTS TO ACHIEVE INCREASED FLOW OF MUCH-NEEDED OIL SUPPLIES IS SUMMED UP IN THE FACT THAT THE AVERAGE HOURLY RATE FOR TANKER DISCHARGE IN GREAT BRITAIN WAS INCREASED FROM 100 TO 450 TONS.



WATER TRANSPORT WAS AN IMPORTANT FACTOR IN PETROLEUM DISTRIBUTION DURING THE WAR AS THIS SCENE AT ONE OF THE BOARD'S OIL WHARVES SHOWS.

come to mind were the invention of the waterproofing system that enabled vehicles to be landed in France through 4½ ft of water : the development of white spirit for use in the paint and ancillary trades as a substitute for the unobtainable turpentine : the extensive replacement of petroleum fuels by creosite/pitch mixture, and many others : so much so that the industry was called upon to assist in national problems without number throughout the duration of the war.

The Decisive Effort.

One may speak with justifiable pride of the part played by the Board in making D-Day possible. One of its most valuable contributions was to the preparatory organization, where there much hard work and little glory. Of necessity, this was at the time shrouded in " security " silence, and as history after the invasion was packed with military drama, little public attention was ever rested on the less spectacular, but vitally important, achievements in the planning stage. There was, for instance, the marshalling of the countless " little ships," that kept the seas open for Britain on D-Day, an enthralling story in itself. To permit the secret mobilization and deployment of these small craft, operating from widely dispersed and concealed bases, fuelling points in all sorts of out-of-the-way and innocent-looking spots were extemporized. Time, material, and labour were all in short supply. As there was not nearly enough pumping equipment to go round, gravity-feeding had somehow to be contrived in most cases, and the countless problems of suitable siting and secrecy of working caused the Board's experts many sleepless nights.

One precaution taken to provide against any conceivable interruption of naval fuel supplies was that of " doubling up " on the Admiralty's own installations. For instance, the Board set up at Portslade a fuelling station which could take over at a moment's notice the supply obligations of the Admiralty's storage at Newhaven : similarly, Hamble was in readiness to " stand in " for the great naval fuelling station at Portsmouth : this was in addition to Hamble's own allotted role in fuelling landing and coastal force craft, loading tankers, and relaying supplies to subsidiary stations along the coast such as Poole, Lymington, and Shoreham.

The " doubling up " scheme naturally involved the duplication of stocks as well as of facilities. As potential requirements under emergency conditions could never be clearly defined, wide safety margins were essential at all points, and as the Board was answerable for stocking both its own and certain Admiralty installations, its burden of responsibility was very great indeed.

Apart from all this, the Board had the special task of preparing the large fleet of fuel-supply ships for their cross-channel voyage. These at first consisted of small vessels carrying packed supplies, with bulk tankers following at a later stage. Actually, the most strenuous labours in this sphere came after the initial landings, for within the first two months of the Normandy campaign Hamble alone was instrumental in effecting the running repairs and turn-round of some 150 ships, a feat personally acknowledged and praised by the Commander-in-Chief at Portsmouth.

The provision of aviation fuel and oil for the Allied air forces was again one of those massive achievements in organization which did not always

lend itself to dramatic detail. The story of the crushing of German military might under the mounting weight of the Allied air offensive can perhaps be most vividly illustrated by the figures for monthly deliveries of aviation spirit. During the first half of 1944, including shipments made abroad, the tonnages soared from 201,000 in January to 535,000 in June. The corresponding figures for 1940 were, January, 15,000 tons and June, 36,000 tons.

Such figures are impressive enough, but they convey no adequate idea of the practical difficulties which had to be overcome. The maintenance of supplies of aviation fuel on this colossal scale presented certain unique problems. For one thing, the immense acceleration in fuel requirements following the Quebec Conference in 1943 necessitated the construction of much additional storage capacity at distribution points, with its ancillaries in the shape of extended sidings, additional rail gentries, road loading bays, and pumping equipment. Shortage in the latter particular was a serious handicap, for at times of intensive demand, loading inwards and outwards took place simultaneously, entailing the use of two sets of pumping equipment. Remembering that this period of feverish activity was also one of grave material shortages and war-time dislocation, it is not a matter of surprise that at no time was sufficient storage available to permit stocking up on a scale commensurate with the almost fantastic current needs. Replenishment of fuel supplies to support the great air offensives was therefore a hand-to-mouth process. Storage capacity at many points was often merely sufficient to cover a day or two of peak demand. Offtake varied wildly from day to day, a vagary worsening with the advent of the U.S.A.A.F., which involved much larger concentrations of aircraft than anything hitherto known. Such was the added strain on the fuel-supply organization that it was decided to adopt the " ullage " system, whereby stock replenishment was aligned with the day-to-day offtake at each point. This demanded an extraordinarily efficient and flexible working arrangement between depots, which were repeatedly called upon to help each other out when the run on stocks affected individual supply points with particular severity.

The successful operation of the " ullage " system was one of the Board's major triumphs, which exacted its price in unremitting toil and anxiety. I have earlier paid tribute to the immense value of the pipeline network which came into operation late in 1943, but in fairness to other branches of the Board's distribution service, it should be pointed out that, since storage capacity was so limited and pipelines do not expand and contract in accordance with military dictates, the bulk of the ultra-normal demands of the later war years had to be implemented by rail and road. Responsibility for the final stage of delivery to aerodromes rested, to a great extent, on the road-transport arrangements. The railcar service did much good work in long-distance distribution, carrying in 1944 over 3 million tons of aviation spirit, or nine times the rail-borne tonnage in 1940. Special distribution railheads were commonly employed, and to keep these in economical operation, train transit and turn-round times had to be cut to a minimum. To take the utmost advantage of daylight hours, all grades of staff laboured long and hard. Of the great part played by the mobile workers I have already spoken.

Difficulties were multiplied by the changes in the supply picture which continually occurred, and by the short notice given of emergency requirements. One especially harassing situation of this nature occurred in March 1944 when the Service authorities suddenly reversed their previous decision to take charge of all deliveries, which were to be on a packed basis, to the Advanced Landing Grounds established in anticipation of D-Day. The Board, at the eleventh hour, was asked to be fully responsible for maintaining deliveries in bulk. To make matters worse, the existing bulk facilities on these grounds were totally inadequate, a deficiency which the Board's organization was called upon somehow to overcome. Even without the necessary supply of tools, our people contrived, as always, to "finish the job," although it must be said that the U.S.A.A.F. provided invaluable aid at this critical juncture.

Some of the most colourful chapters in the Board's war-time history followed as the Liberation campaign swung into its full stride. You will all recall those momentous days in the early autumn of 1944, when General Patton's columns hurtled across France on the right flank of that amazing Allied advance which bid fair to end the war before Christmas. Yet in its very pace lay the seeds of failure, for the outrunning of motor-fuel supplies literally stopped the armoured columns in their tracks. The American High Command, with that almost sublime faith in the powers of British civilian authorities which it repeatedly displayed, flew a special mission to this country to consult Petroleum Board experts. Could the impossible again be achieved?

Within two hours of that emergency meeting, our men had drawn up a complete working plan to supply motor fuel to the advance battle areas direct by air from this country, employing Liberators specially equipped with bomb-bay tanks of 2000-gallon capacity. Time-saving being all-important, many of these were loaded straight from standing railcars. Suitable aerodromes had to be switched solely to this supremely urgent task. Hundreds of thousands of gallons daily were flown to France by this unrehearsed "air-lift" method.

Regrettably, the improvised French landing grounds were in such poor shape that large and heavily laden aircraft could not use them on anything like the requisite scale. The gallant adventure therefore petered out, but not before the Petroleum Board had proved its capacity to justify yet again the confidence of our American allies.

Another period of intense and exciting activity came even later. After the surprise counter-offensive by Von Rundstedt's armies at the end of 1944, the Allies prepared the way for the final assault by aerial battering of unparalleled and sustained ferocity. At the same time, a prolonged period of fog threatened to keep the bombers grounded, and only the intensive employment of FIDO apparatus enabled them to maintain operations. So, on top of the aviation-fuel problem, it was necessary to bring trainload after trainload of FIDO fuel to the air bases concerned. Once again, even under these well-nigh heartbreaking conditions, the Board never let the air forces down, and aviation-fuel deliveries effected in March and April 1945 outstripped all previous records.

Much could also be said concerning the key part played by the Board in fuelling the British and American land forces engaged. This work

began long before the Normandy plan matured, and affected all Regions, even those remote from future operations. There were battle-training grounds, Commando training depots, training centres for Combined Operations, all requiring to be kept supplied with fuel, often at short notice and under unfavourable conditions. Mention should also be made of the fine job done by the bunkering fleet, which moved oil to a total of something like 8½ million tons during the war. This figure, of course, takes no account of the enormous quantities supplied for bombers direct from shore storage.

Those fateful days, anxious and stressful though they were for all concerned, were not without their lighter moments. Could any incident have been more fantastic than the fine solemnly inflicted on one of our drivers for exceeding the speed-limit when delivering an express load of aviation spirit on D-Day: or more absurdly ironic than the enforced immobilization of some of our most urgently needed drivers and vehicles on a U.S.A.A.F. aerodrome for "security reasons"?

A word on communications. We undoubtedly had our excellent system to thank for much information that came our way. It is a little known fact that the Petroleum Board had its own teleprinter system operating before war actually broke out. This system enabled messages to be sent instantly to and from the Board's Regional Offices and Installations and also British refineries. As many as 5000 messages were handled by the system in a day, and the service was manned for twenty-four hours a day throughout the whole war.

Conclusion.

"Twenty-four hours a day" is an expression that summarizes very well the duties and the outlook of the Petroleum Board organization. There was never a moment during the war when the organization was static. Some part of it was always pressing on towards a new development—mostly, I may add, developments in advance of their being required. One was never able to sit back and say, "Well done. Now we can take it easy." Always, there was the task ahead beckoning for action, often a task that had never been done before.

It says much for the flexibility and ingenuity exercised by the various departments of the Petroleum Board that, in ability to meet a crisis, whether it was one of organization or invention, it rarely, if ever, had to admit that it was beaten by a problem.

Credit is due to the men, at all levels, who manned the Board, and saw that it worked. Credit is also due—and let us not be too modest about it—to a great industry, built up on the basis of competitive efficiency, which bred the men, their knowledge and intitiative, possessed the resources, and placed all three voluntarily at the service of the nation in the greatest military struggle of its long history.

The Government, with its comprehensive knowledge of both military and civilian requirements, was naturally in the best position to take the overall strategic decisions. Having taken them, it wisely let the people who knew how to do the job get on with it.

These were the true foundations of the industry's high achievements, and I count it a great privilege to have participated in them.

THE INSTITUTE OF PETROLEUM AND THE INSTITUTION OF CHEMICAL ENGINEERS.

A JOINT meeting of the Institute of Petroleum and the Institution of Chemical Engineers was held at Manson House, 26 Portland Place, London, W.1, on Monday, February 23, 1948.

PROFESSOR F. H. GARNER, O.B.E. (Past-President of the Institute), presided and in opening the meeting, said: This is one of the first Joint Meetings of the Institution of Chemical Engineers and the Institute of Petroleum we have held for some time, but I hope that in future many more joint meetings of the two bodies will be held.

It is rather a remarkable fact that the rapid growth of chemical engineering dates to the time when the petroleum industry began to apply scientific methods to petroleum, that is to say, the renewed interest and growth has occurred within the last 30 to 35 years. Although the fundamental principles of such subjects as we are discussing date back a very long time—Boyle's law to 1662, Henry's law to about 1830, and Raoult's law to about 1880—nevertheless it is only comparatively recently that we have seen a detailed study of the phenomenon of vaporization.

In the paper Mr Baars gives details of a pipe still dating back to 1910; but, of course, the pipe still was used in the distillation of coal tar as early as 1893.

We are much indebted to Mr Baars for having made a special visit here to present his paper.

MR BAARS then read the following paper:—

VAPORIZATION IN FURNACE TUBES.

By G. BAARS. (Fellow).

A SERIES of lectures on the flow of liquids and gases, delivered to the Petroleum Section of the Royal Institute of Dutch Engineers in 1938, provided the occasion for the preparation of this paper in order to explain the importance of acquiring more knowledge regarding the flow of liquids and vapours in furnace tubes.

Before tube furnaces were put in use, oil was heated in cylindrical vessels placed over a fire-box, with or without internal flues. These shell stills were initially batch distillers and consequently worked intermittently. After filling, the temperature rose, and first the light fractions and then successively heavier fractions distilled over. There was no heat economy and on this account continuous working batteries superseded batch operation. Then each still could be maintained at its own temperature and delivered its own fraction.

The heat transfer rate for such a battery of stills was 3500–5000 B.Th.U/sq ft/hr max. The maximum permissible temperature was about 600° F. The last battery of this type was built in 1927, when it

was generally accepted that the tube furnace would be the heater for the future.

In the cylindrical stills no turbulent flow could be developed and it was not until several years later, when old stills had been modernized with spray-jets on the flues—in the same way as was done in the Stratford furnace of the Lobitos distillation plant—that this became possible.

The tubular furnace is built as a bank of tubes placed over or around a fire box or in a flue. Tubes are of such a size that the flow therein will be turbulent. Heat is transferred by radiation and convection.

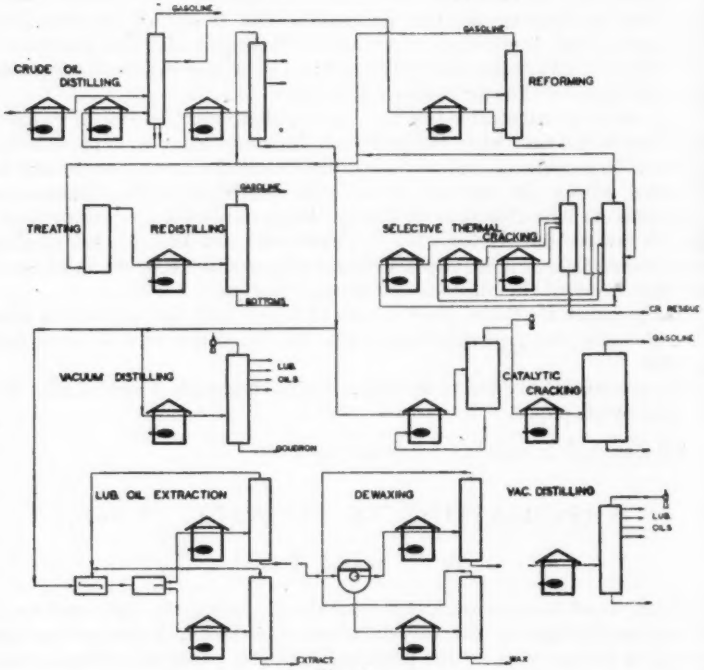


FIG. 1.

FURNACES IN PETROLEUM REFINERIES.

The first furnaces were used in order to vaporize the total quantity of distillates contained in the crude oil. The oil was separated from the vapours in an evaporator and these vapours were fractionally condensed. Gradually this type of furnace has been used for many other purposes such as for heating, reboiling, and the recovery of solvents from oil mixtures, etc.

In order to give an idea of the importance of the tubular furnace it should be mentioned that 8 to 12 per cent of the crude oil is required for heating these furnaces, which means a total fuel consumption of about 1 million barrels per day.

The scheme of a modern refinery (Fig. 1) shows the duties for which these furnaces are used.

The first furnace, built in 1911 (Fig. 2), consisted of a combustion chamber in which were fitted a number of 12-inch tubes connected with 4-inch return bends. In the light of the present knowledge of the conditions involved it is obvious that this furnace could not meet the requirements, because the vapour produced was unable to escape from the wider tubes via the narrow bends.

In course of time different types of furnaces were constructed. All

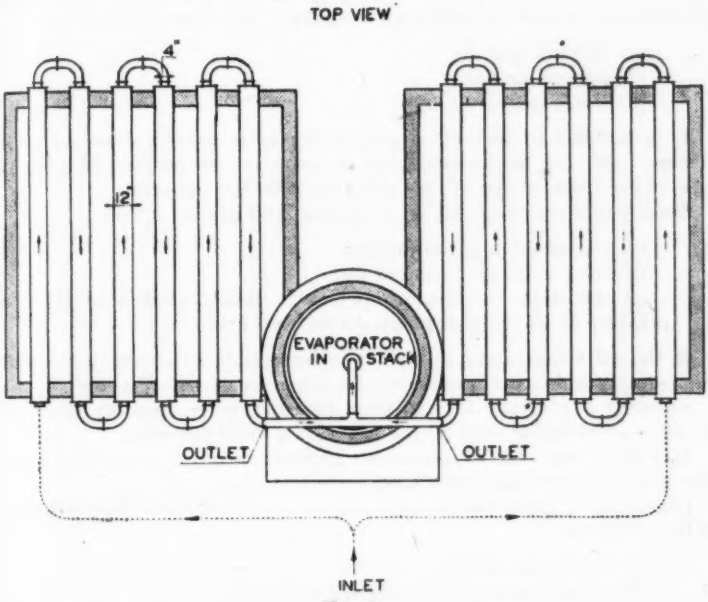


FIG. 2.

THE FIRST FURNACE BUILT FOR FELLOWS PLANT IN 1911.

were constructed on the same principle. Walls and arches were supported by a steel framework and formed the combustion chamber in which the tubes were placed. These tubes were supported by alloy steel hangers and supports.

Burners were fitted in the side walls, floor, or roof of the furnace. Theoretically the furnace with roof burners should be the steadiest in operation; gases in process of cooling become heavier and there is thus a natural tendency for them to descend.

A great difference in pressure between the combustion chamber and the atmosphere is undesirable as air leakage cannot in this case be controlled. Special care should be taken to ensure that the brick setting of the furnace should be as tight as possible.

Detrick and Bigelow Liptak constructions for furnace walls and arches

are in common use. The composition of the fire bricks will in some cases need to be specified in relation to the properties of the fuel.

Some manufacturers use insulating fire bricks, which are of low specific weight, thereby reducing the total weight and cost of the furnace.

The walls and arches are usually covered by a layer of insulating material, followed by an air insulation from which the outside air is excluded by steel sheets.

The firing calculations for the combustion chamber are identical with those used for water tube steam boilers. The heat generated by the fuel has to be transmitted to the oil flowing through the tubes with as high an efficiency as possible, and may be divided into three main groups:

(1) radiant heat;
(2) convection heat;
(3) stack losses.

It is possible to plot these graphically as is usually done for steam boilers. The use of the triangular diagram is also possible because the sum of the three groups of heat will always be 100 per cent.

Stack losses vary from 15 to 35 per cent and depend upon:

(*a*) construction of the furnace;
(*b*) the percentage of excess air;
(*c*) the stack temperature (which is closely related to the temperature at which oil is pumped into the furnace).

If the oil temperature is high it is impossible to attain a low stack temperature unless other measures are taken to ensure efficiency.

Allowing 5 per cent for radiation losses, tubular furnaces thus have an efficiency ranging from 80 per cent down to 60 per cent.

In view of the enormous amounts of fuel consumed a careful study of the efficiency problems is justified.

Considerable quantities of heat can be recovered from the stack gases if they are used

(1) to preheat the oil;
(2) to heat water or to producing steam;
(3) to preheat the necessary combustion air, as a result of which the temperature level throughout the combustion chamber will rise.

If the stack is made of steel the temperature to which the combustion gases may be cooled is limited by the occurrence of condensation in the stack, giving rise to corrosion.

The type of burner selected is also of importance, depending on whether the firing is with gas, oil, or asphalt, and whether a long or a short flame is required.

The heat generated by the fuel is partly absorbed by radiation, in the case shown in Fig. 3, for instance:

firstly by the tubes in the combustion chamber, and
secondly by the top rows of tubes in the convection section;

and furthermore by convection in the bank of tubes of the convection section.

In the same way as with steam boilers the mean temperature of the combustion chamber is taken to be the temperature at which the combustion gases leave the combustion chamber.

In the Stephan Bolzman formula the radiation factor in this case will be higher than the theoretical one. However, this value is only used as a comparison factor.

The average load of a furnace combustion chamber is 7,000 to 14,000 B.Th.U/cu. ft/hr, whereas this load for boilers has already reached a figure up to 280,000 B.Th.U/cu. ft/hr.

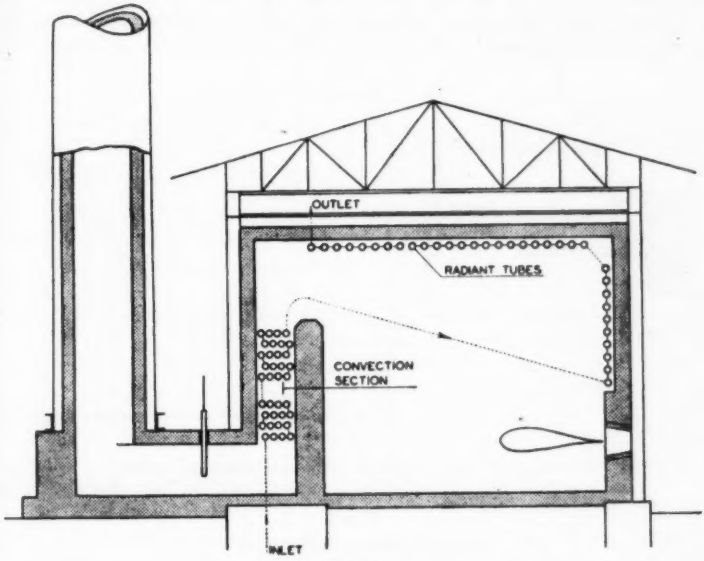


FIG. 3.

RADIANT AND CONVECTION TYPE FURNACE.

There is, however, a tendency to change to higher loads in order to reduce the cost of the furnaces, but on the other hand a larger combustion chamber is recommended with a view to good heat distribution and minimum maintenance cost.

All the factors mentioned above should be taken into account before a proper heat distribution in the furnace can be affected.

An average value for the heat absorption by radiation is 7,000–13,000 B.Th.U [4]/sq. ft/hr calculated on the full tube surface.

The size of the convection section is calculated by using the logarithmic mean difference in temperature between gases and oil at inlet and outlets. The k value varies from 5 to 8 B.Th.U/sq. ft/°F/hr and depends upon the arrangement of the tubes and the velocity of the combustion gases.

The heat distribution over the furnace tubes is the first step towards calculating the pressure drop in the furnace tubes.

Let us now examine what happens to the oil as it is pumped through the furnace tubes. It will follow successively all the tubes from the inlet to the outlet of the furnace just as it would follow a continuous single tube. At the entrance the flow may be streamline, but as a result of the increase of temperature the viscosity improves, the volume becomes greater, and the Reynold's number increases, so that the transition zone is passed and the flow changes from streamline to turbulent. More heat is absorbed and at a given moment bubbles of vapours occur, small bubbles will unite to larger bubbles, and as vapour is lighter than liquid these bubbles will collect at the top of the tube.

Vaporization is promoted not only by increase of temperatures but also by decrease of pressure. Vigorous bubbling sets in and, as long as the

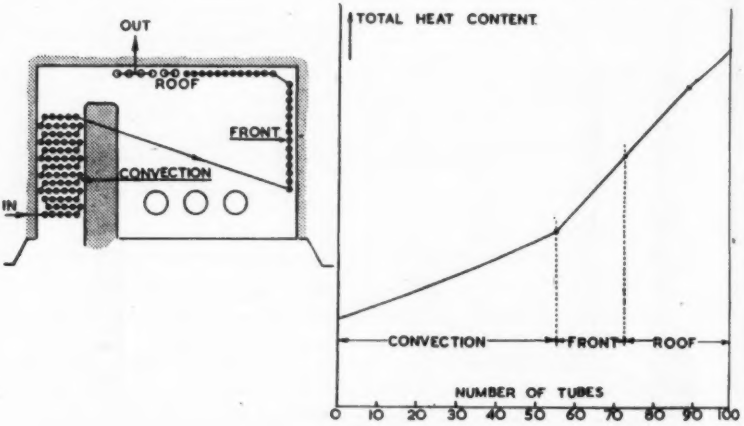


FIG. 4.

HEAT ABSORPTION IN FURNACES.

liquid remains in the continuous phase, it is in the foam condition. Fortunately this condition is of brief duration, for the continuity of the liquid phase ceases when 52 to 74 per cent of the tube volume is occupied by vapour bubbles. Then the mist condition ensues.

Still the pressure continues to fall and heat is added, with the result that particles of liquid coming in contact with the tube wall will easily vaporize. This vaporization may be carried on until there is no more liquid in the tube. The vapour is now dry and if heating is continued beyond this stage it will become superheated until decomposition commences. This decomposition entails expenditure of reaction heat and cracking takes place in the vapour phase.

Cracking may also occur when vaporization is arrested (by increase of pressure), giving rise to such a high temperature as to cause decomposition. In this case cracking in the liquid phase takes place.

In this paper we are, however, only dealing with furnaces in which partial vaporization takes place and the temperature remains below 400° C, so that no cracking occurs.

In the design of a tubular furnace not only do the factors necessary to ensure a good heat distribution have to be borne in mind, but consideration has also to be given to the temperature and pressure characteristic and the correct location of the vaporization zone.

It will be shown that the highest temperature is not always that at the furnace outlet and that the greatest pressure drop is not usually formed in the vaporization zone.

The phase at which vaporization commences is of prime importance, and is determined not only by the condition of temperature and pressure but also by the properties of the oil passing through the furnace.

It is, therefore, firstly essential to know the temperature and pressure characteristic of the oil in the furnace before a fair opinion can be given on the design.

The available literature on the subject is as yet insufficient to afford a guide to accurate calculation, but the following is extracted from " Petroleum Refinery Engineering " by W. L. Nelson, under the heading " Pressure drop in pipe stills " (page 257) :

> *" The application of flash-vaporization data to the problem of computing the vaporization that occurs within pipe still tubes is complicated by the constantly changing pressure throughout the entire length of pipe-still tubing.*
>
> *" However, vaporization usually does not occur until the final tubes of the still are reached, because as soon as vaporization starts, the friction loss and the pressure become so high that vaporization is suppressed. In fact a large part of the pressure drop through a pipestill often occurs in the transfer line from the still to the fractionating tower. To shorten this line does little good because the vaporization is simply pushed back into the still. Likewise a larger transfer line decreases the pressure at the outlet of the still, so that more vaporization occurs in the tubes.*
>
> *" The pressure drop can be estimated by considering the heating coil as being broken up into a series of coils, each of which heats the oil for a temperature range of about 10° F and operates at a different pressure. By trial-and-error solution, the length of each section of coil can be computed (working progressively from the pipe still outlet) by assuming the pressure and/or length, computing the vaporization from a flash-yield curve at the assumed pressure, and checking the pressure and/or length from the friction loss of the fluid. The method is sound if adequate physical data are available, but it is a tedious procedure."*

While this gives some data it does not give temperature and pressure characteristics obtained by actual readings. Curves have been presented (*Oil Gas J.*, 5.7.47, 46 (9), 93), but a note is made that information about pressure drops through heaters is important and its calculation is difficult.

For the pressure drop calculation of that part of the furnace tubes in which only liquid is flowing the so-called Fanning equation can be used :

$$(dF/dL = 4fV^2/2gd)$$

f can be found with the help of the Reynold's number, for which the viscosity is required.

The pressure drop calculation for the foam range, which follows after the liquid range, will not be dealt with for the time being. Later on it will be shown that the pressure drop in this part will not be of great importance.

For the pressure drop calculation of the mist range the Fanning equation may also be used if the mist is considered homogeneous, so that the liquid particles acquire almost the same velocity as the vapour.

Before going further into the pressure drop calculations it is essential to know how much vapour will be formed under certain conditions and under continuous operation if the oil flowing through the tubes is known. For this purpose, the vaporization characteristics of the oil at given pressures and under continuous conditions must be ascertained. The following properties of the oil should also be known:

(1) Nature of the oil (asphaltic, paraffinous, etc.);
(2) Specific gravity;
(3) Pourpoint;
(4) Viscosity;
(5) Distillation curve, if possible over the whole range from I.B.P. to F.B.P.

This distillation curve may be determined by the usual A.S.T.M. method of plotting the volume percentage distilled as a function of the vapour temperature.

A far more accurate method is that whereby a very good fractionating column is used by which a very small amount of the condensed top vapours are released as top product and the remaining distillate is returned into the column. In this way the ascending vapour is brought into close contact with the descending liquid and the vapours are stripped of the heavier portion that would tend to be entrained. The distillate released will thus be much purer than with A.S.T.M. distillation. The distillation curve obtained in this way is referred to as a "true boiling point curve" and is usually plotted in weight percentages. It is consequently necessary to determine the specific gravity of the successive fractions. The fractions produced in the refinery plants will not be of so high a purity.

The distillation curve given in the left-hand diagram of Fig. 5 is a flowing line drawn through a true boiling point curve for a crude oil. This curve represents the entire boiling range from the I.B.P. up to the F.B.P.

In addition there are plotted (in dotted lines) the distillation curves of two fractions which, if put together again, would give the same composition as the crude oil. These fractions are produced in practice by means of fractionating columns. The F.B.P. of the light fraction will be higher than the I.B.P. of the heavier fraction. This difference in temperature is called the overlap.

In order to ascertain the separation of liquid and vapour in the furnace tubes we have to compare this with simple continuous distillation, *e.g.*, in an evaporator when oil heated sufficiently to cause partial vaporization is continuously pumped into it. In this way the oil would be separated into two fractions and the temperature by which it is vaporized determines where the dividing line will be. If true boiling point curves of the

top and bottom products were to be plotted they would overlap far more widely because no rectification has taken place.

We thus see what happens when oil is vaporized under continuous conditions.

The temperature in the evaporator will adjust itself in accordance with the pressure and composition of the inflowing oil. When the composition of this oil and the quantity in percentage distilled off are known, this temperature can be calculated.

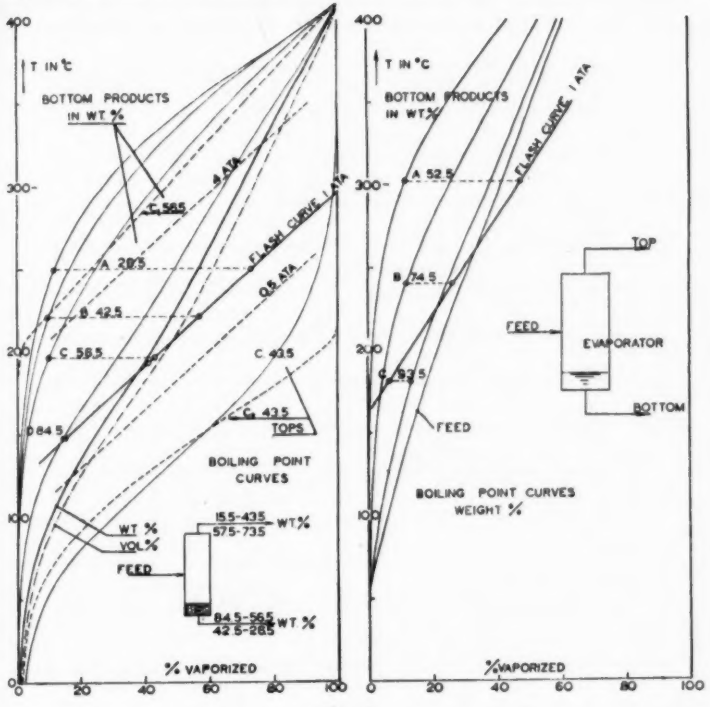


FIG. 5.

FLASH DISTILLATION CURVES.

These equilibrium temperatures have been calculated in succession for cases in which the percentages of remaining liquids are respectively 84·5, 56·5, 42·5, and 28·5 per cent, representing 15·5, 43·5, 57·5, and 71·5 per cent distillate.

The boiling point curves have been drawn for the remaining liquids. For only one of these cases—viz. that in which 43·5 per cent has been vaporized—has the boiling point curve of the distillate been given.

Attention is drawn to the considerable overlap which exist between the two relating fractions.

If the percentages of vapour produced are plotted against the calculated

temperatures of equilibrium, we obtain a new curve which in many cases will be almost a straight line and which is called the flash curve.

Each flash curve is applicable for only one particular pressure.

Flash curves for higher or lower pressures can either be calculated or be established with the aid of vapour pressure graphs.

A flash curve alone does not therefore give any indication concerning the composition of the fractions produced. The separation of the two fractions is in agreement with that of simple continuous distillation.

Flash curves may prove very helpful for indicating the amount of vapour that is formed in the furnace tubes under specific conditions.

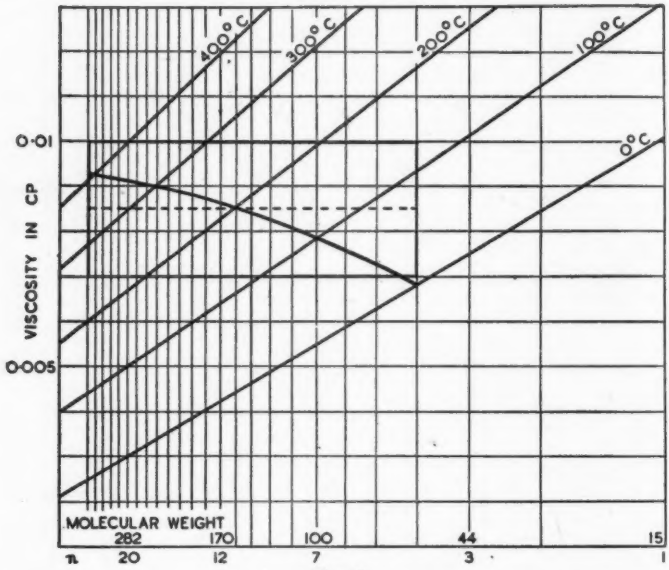


FIG. 6.

APPROXIMATE VISCOSITY OF OIL VAPOURS IN CENTIPOISES AT 1 ATM. ABS.

Thus the flash curve for the conditions at the furnace outlet can be drawn.

As a rule the mist condition will be prevalent at the outlet and so the normal Fanning equation for calculating the pressure drop can be applied with the weight of material flowing, the percentage vaporized, the molecular weight of the vapour, the temperature, the pressure, the tube diameter and length, the total volume can be calculated and hence the specific weight.

For determination of the Reynold's number the viscosity of the flowing material at the given location is also required, and no serious error will be made if the viscosity of the vapour is taken for this value.

The viscosity has been plotted in centipoises in Fig. 6 as a function of the molecular weight.

In view of the slight influence exerted by the Reynold's number upon the coefficient of friction a correction for the viscosity of the liquid vapour mixture will not be introduced for the moment. With the Reynold's number calculated the coefficient of friction can now be ascertained by means of the well-known graphs.

In the pressure drop calculation it will be necessary to introduce the resistance length of straight tube equivalent to one return bend. This resistance length depends upon the shape of the bend. A streamlined return bend will have a lower resistance than a square box type.

CASE	TEMPERATURE	PRESSURE (OR ΔP)	% VAPORIZED	HEAT CONTENT
1	X	X	–	–
2	X	–	X	–
3	X	–	–	X
4	–	X	X	–
5	–	–	X	X
6	–	X	–	X

IF PRESSURE DROP HAS BEEN ASSUMED THE PRESSURE IS FIXED.

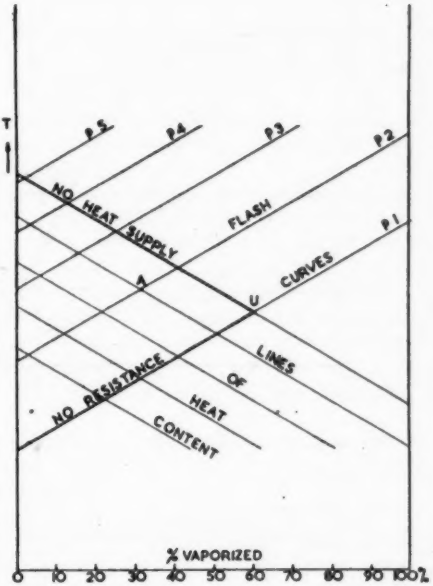


FIG. 7.

This equivalent length may be assumed to range from 18 to 30 feet.

With the Fanning equation the pressure drop in one tube plus return bend can now be calculated for the conditions as at the furnace outlet.

In order to start the vaporization curve in the temperature–vaporization per cent diagram, it will be necessary to assume a second point in addition to the condition point for the furnace outlet. This second point will indicate less vaporization, because it will represent the conditions at a position located a few tubes before the outlet of the furnace is reached.

By assuming this hypothetical point of the curve the following are also assumed :

(1) the temperature;
(2) the pressure;

(3) the amount vaporized; and consequently,

(4) the quantity of heat available in the flowing stream at that station.

With these four factors there are six possibilities as shown in Fig. 7. The location of one point of the temperature–pressure curve is fixed by two factors. Which of these factors can be assumed with the greatest degree of certainty needs to be considered.

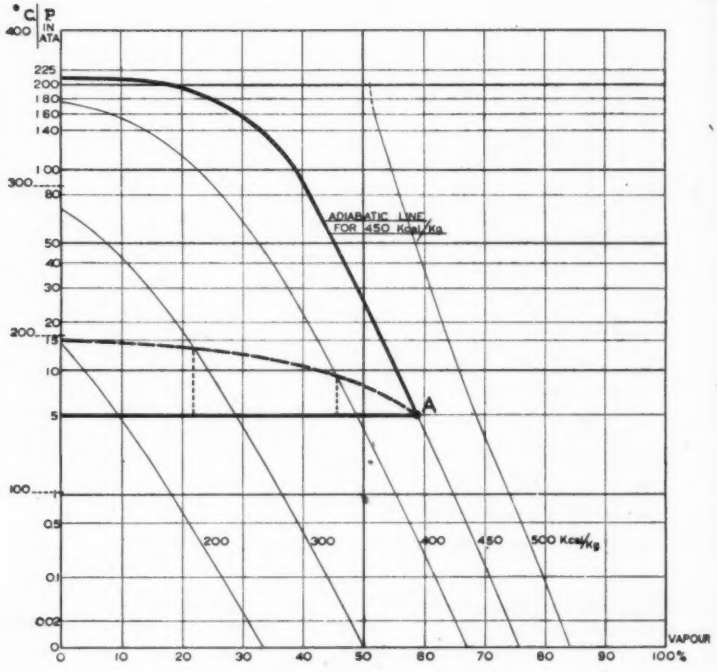


FIG. 8.

EVAPORATION OF WATER.

To assume the *temperature* is very difficult, for it is not known whether the temperature at the new position will be higher or lower than at the furnace outlet.

To assume the *pressure* means also to assume the pressure drop between the pressure at the new position and the pressure at the furnace outlet. This is quite possible, because it can be based on the pressure drop of one tube plus return bend as previously calculated for the conditions at the furnace outlet.

To assume the amount vaporized is just as difficult to determine as the temperature, although the quantity of heat available in the flowing stream at the assumed station will be known from the heat distribution

in the furnace, so that this heat content can be read at any desired position.

Before drawing the curves of constant heat content in the temperature–vaporization diagram, this can be illustrated by an example in connexion with water and steam.

In the graph (Fig. 8) drawn for this purpose the temperature has again been plotted as ordinate and the percentage evaporated as abscissa.

When water is heated to, say, 370° C, a pressure of at least 213·5 kg/cm^2 will be needed to prevent this water from evaporating.

If the pressure is reduced, however, while the heat content remains constant, the evaporation curve will be an adiabatical one and will follow the lines of equal heat content.

Water cannot be heated to such a high temperature that when the pressure is released all the water evaporates. The latent heat of water with respect to the specific heat is too great to permit of this.

Complete evaporation of the water is only possible if heat is added during expansion as indicated, for instance, with the dotted curve to point *A*.

If the heat supply is added to the water through one continuous pipe, a certain resistance will be created in the pipe, depending upon the amount of water and steam passing, and this resistance will check evaporation at the beginning of the pipe. The temperature at the beginning of the pipe will therefore need to be higher in order to initiate evaporation.

Attention should be drawn to the very steep course of the lines of equal heat content and the flash curve which, in the case of water, runs horizontally. Water has no boiling range.

Reverting to the tubular furnace, a similar diagram can be drawn for this case.

For the furnace outlet the heat content of the partially vaporized oil is known and is the sum of the heat contents of the oil in liquid condition and the heat content of the oil vapour.

From the data for the heat contents of oil liquids the temperature at which the oil would contain the same heat with no vaporization at all can be determined, and in the same way any intermediate temperature covering the whole range from 0 to 100 per cent vaporization can be ascertained.

The lower the heat of vaporization the less steeply the lines of equal heat content will run.

Although these lines will not be absolutely straight they are here assumed to be straight, as the error made with this will be negligible.

Just as the line of equal heat content for the furnace outlet was found, so can this same characteristic be plotted for any other station in the furnace.

In order to arrive at the conditions prevailing at the furnace outlet various procedures may be used.

The temperature might have followed the flash curve, but in that case the resistance throughout the range extending from the point when vaporization commences to the furnace outlet would have to be nil.

The temperature might also have followed the line of equal heat content, but this would mean that no heat absorption would have taken place throughout the whole range mentioned before.

These two cases establish the limits of the conditions via which the condition prevailing at the furnace outlet can be reached.

In this way, too, the maximum pressure will be determined at the place of commencement of vaporization. This pressure cannot be higher than that corresponding to the flash curve passing through the point of intersection of the maximum heat content line and the axis of zero vaporization.

It is of importance to know this, for in certain circumstances, when only the total pressure drop in the furnace is required, the calculation

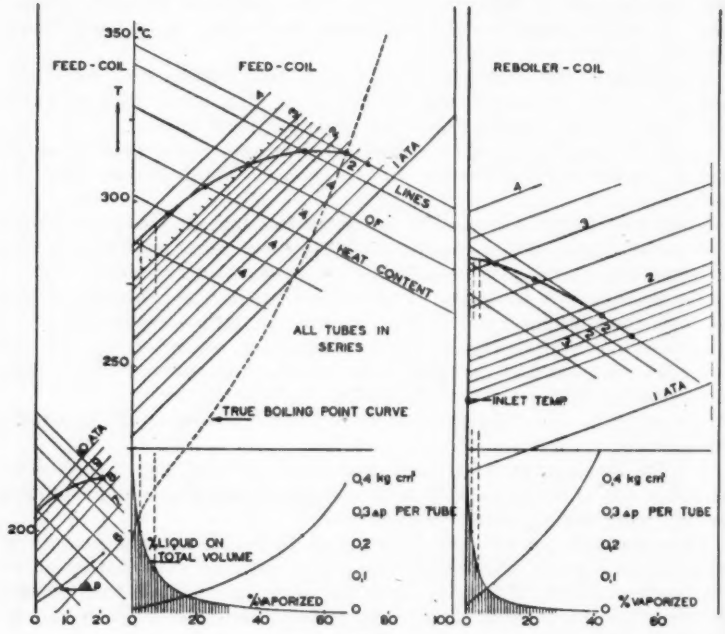


FIG. 9.

FURNACES FOR CRUDE OIL DISTILLATION.

could be discontinued at this point, since these data, regarding the range in which vaporization takes place, may be sufficient for practical purpose.

In any case it is now known that the temperature–pressure curve in the vaporizing zone must be located inside the triangle explained before.

Inside this triangle there are not only flash-curves for different pressures, but also lines of equal heat content for positions at which conditions must be further determined.

Fig. 9 shows some available examples for furnaces operating under pressure as well as operating under nearly atmospheric outlet.

The triangles of axis flash curves and line of equal heat content can at once be recognized.

The pressure drop for one furnace tube plus return bend has been plotted for the conditions at the furnace outlet. The pressure drop from the first position to the furnace outlet has to be assumed. With the aid of this pressure drop, the pressure at the first position has to be established.

Assume this station is located three pipe length from the furnace outlet and that the heat content is known it will be possible to draw the line of equal heat content. Further, it will be possible to draw the flash curve belonging to the pressure at this first position.

The point indicating the full condition for the first station is thus the point of intersection of the line of equal heat content and the flash curve for the assumed pressure.

The percentage vaporized and the temperature at the first station is thus established and consequently the following can be calculated :

The volume;
The specific weight; and
The velocity

of the material passing through, and hence we can also determine the pressure drop in one furnace tube plus bend for the conditions prevailing at this position.

The mean resistance over the range from this position to the furnace outlet will be

$$\Delta p = \frac{R_{out.} + R_{st.}}{2} \times \text{number of tubes.}$$

If the calculated value of Δp does not check with the assumed one it will be necessary to make a new estimate until the deviation shown by Δp becomes negligible.

In order to facilitate the assumption of pressure drops a curve has been plotted giving the pressure drop in one furnace tube plus return bend over the whole range of vaporization.

We can thus work from position to position.

The largest changes are, of course, in the vicinity of the furnace outlet; therefore, in order to permit proper calculation of the course of events, the first station should only be, say, two or three tube length away from the furnace outlet.

Wherever drastic changes may be anticipated, it is advisable to take shorter intervals between positions.

Besides the pressure drop per tube also the amount of liquid as a percentage of the total volume has been plotted in these diagrams to show the behaviour of the material passing through during increasing vaporization.

This latter curve shows that only at a low percentage of vaporization (4 to 10 per cent) the condition in the furnace tubes will change from the foam to the mist condition, because at that point already more than 74 per cent of the total volume becomes occupied by vapour; furthermore the velocity has then increased to more than 30 ft per second.

The location at which vaporization will commence can also be seen from this diagram.

As already mentioned, the region in which the foam condition (or the

complete separation of liquid and vapour) prevails is a dangerous one, since the bubbles which are formed may become lodged in the tube and give rise to overheating of the tube wall and the oil.

As a rule furnace tubes are positioned horizontally and the bubbles will collect at the top. The heat transmission of vapour is much lower than that of liquid, with the result that tubes which are, for instance, half filled have a tendency to bend upward.

The duration of the foam condition can be found in the vaporization curve. It can also be seen in how many tubes this condition may be anticipated.

If the oil in course of processing is likely to cause difficulties on account of its corrosive nature, the following method may be employed with a view to completely eliminating the foam condition in the tubes.

From the graph it is known at what point vaporization starts, but by increasing the pressure vaporization will commence later.

Therefore if a restriction in the flow would be built in, say by incorporating a narrower section, the vaporization will start later due to the higher pressure before the restriction.

By drawing this condition in the diagram, it will be seen that after the liquid has passed the restriction the heat content may be so high that a certain percentage will vaporize immediately. If this percentage is more than 10 per cent the whole foam range will not occur. By putting in this restriction the liquid flow will be immediately transferred into the mist condition.

This will probably also obviate the separation of liquid and vapour, because the velocity in the narrower section will give rise to atomization.

The greater the boiling range of the oil the steeper the flash-curve will be. On this account the temperature curve, by increasing vaporization of crude oil, will usually show a continual rise all the way to the furnace outlet, notwithstanding the fact that all the tubes are connected in series.

This is not always the case for vaporization of narrow fractions, as happens, for instance, in reboiler furnaces. The material to be vaporized is in these cases usually pumped into the furnace at boiling point, because it comes straight from the fractionating column into the furnace, and here it must absorb a certain amount of heat required for the fractionation in the column.

For such a reboiler furnace the temperature curve by increasing vaporization has been plotted in Fig. 9, and it can be seen that the temperature in the vaporization zone shows a continual fall.

This higher temperature in the tubes has probably never been expected in this type of furnace.

In order to improve the temperature characteristic in this furnace it will be necessary to decrease the pressure drop in the vaporizing section, but as the flash-curve of the material, which has to be reboiled, has only a small slope it will be difficult to obtain a temperature curve that continually increases all the way to the furnace outlet, for the flash curve itself is the lowest limit.

In such a case, therefore, it will be necessary to use tubes of larger diameters or to connect several tubes in parallel in order to obtain the required reduced pressure drop.

It is recommended in such cases that the thermometer controlling the temperature of the furnace outlet should not be placed at the furnace outlet, but should be located at the place where vaporization commences.

Fig. 10 shows another example of an existing furnace for the heating and vaporization of crude oil, with the pressures and temperatures plotted against the number of furnace tubes.

The plotted points in circles represent actually measured pressures and temperatures, which proves that the method of calculation is quite acceptable.

Besides the pressure drop per tube a graph has been shown for the

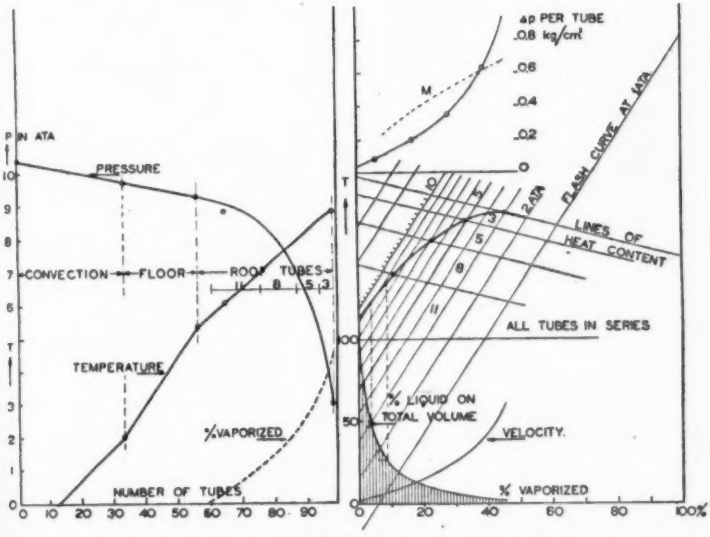


FIG. 10.

FURNACE FOR CRUDE OIL DISTILLATION.

molecular weight of the vapours and the velocity of the material inside the tubes.

The conditions in the transfer line will follow the line of constant heat drawn for the furnace outlet condition, because no heat is supplied and vaporization continues due to reduction of pressure.

In order to ensure good heat transmission in the vaporizing zone it is essential that the inner side of the tube walls be kept wet. Assuming that there would be an oil film of $\frac{1}{60}$ of an inch in the last tube if all the liquid that is present (1 per cent of the total volume) were to flow along the wall of the tube, this would mean that as an average not more than 60 to 70 per cent of the quantity of oil pumped through should be allowed to vaporize.

The author's feeling is that if a higher percentage of vaporization in the furnace would be required and the oil is not too sensitive to tempera-

ture, an additional amount of the heavy fraction should be recirculated so that a maximum of 70 per cent will be vaporized in the furnace tubes.

In a furnace for a high vacuum distilling plant the volume of vapour in the last tube will be very great on account of the low pressure prevailing therein; in addition there may be steam present, which increases the volume still further.

Fig. 11 shows a specific type of furnace in which the outlet is formed by 4 tubes connected in parallel preceded by 2 tubes in parallel and all further tubes connected in series. The furnace is well constructed if its temperature curve is considered. If, however, the velocity in the tubes is observed and specially the last of the series-connected tubes it is found

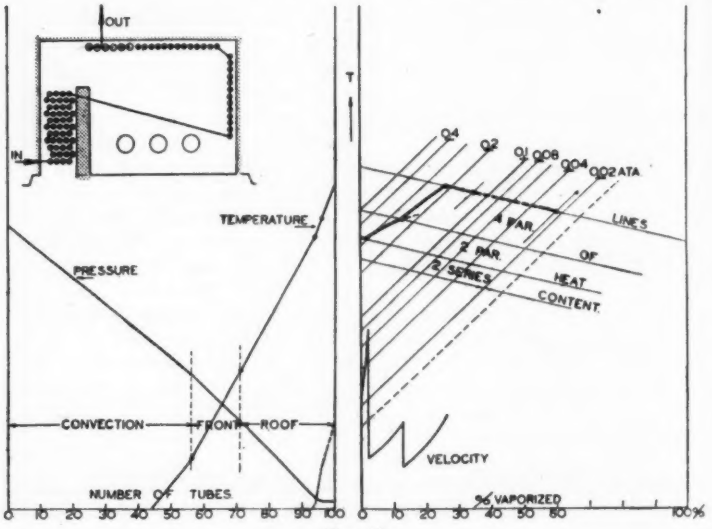


FIG. 11.

FURNACE FOR HIGH VACUUM PLANT I.

that it shows a sudden increase at the point where vaporization commences.

When this same furnace was used for the vaporization of a lighter feed stock the capacity was found to be limited.

Fig. 12 shows the curves for these circumstances and when the diagram is examined the reason is obvious. Neither the pressure drop in the four parallel outlet tubes nor that in the two following parallel-connected tubes gives any cause for comments, but the next tube of smaller diameter demands attention. In this tube the pressure drop is so excessive, due to the fact that vaporization just starts at the beginning and more than 50 per cent has vaporized at the end of this tube. In this one tube the velocity rises from about 6 feet to over 500 feet per second.

Whilst the heat absorption has a normal characteristic, the pressure and temperature curves show an undersirable trend.

The temperature in the last of the series-connected tubes is considerably higher than the furnace outlet temperature, a condition which is not permissible at this temperature level.

It is of interest to know how the tubes behave in this region if they are made of carbon steel.

The tubes shown in the lower half of Fig. 13 give a good illustration of this.

The furnace tube seen in section above them has been effected by partially vaporized sulphur-containing oil.

As mentioned before, the tube arrangement is sometimes compelled to change over from series to parallel connexion.

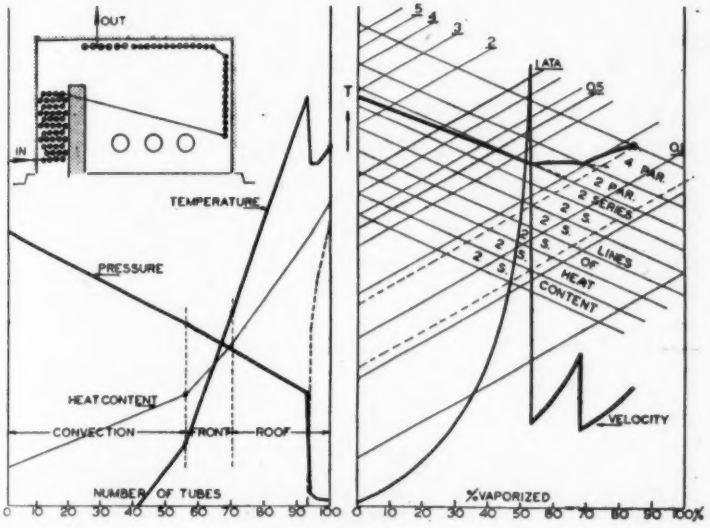


FIG. 12.

FURNACE FOR HIGH VACUUM PLANT IA.

It is important to know just where to do this.

If vaporization has only just started and change-over is effected from a single flow to two parallel flows, there will be a tendency for all the liquid to flow along the most remote side of the return bend and consequently flowing into the most remote tube, whilst the intermediate tube will be conveying only (or practically only) vapour.

This will give rise to uncontrollable increase of temperature, overheating, and tube burst.

Change-over from a single to a double flow should therefore always be effected in such a way that both vapour and liquid are cut into two equal portions.

Fig. 14 gives the diagram of the furnace characteristics of a modern high vacuum plant. The arrangement of the tubes has been made so

that the passages have been enlarged three times by connecting more tubes in parallel.

In this case change-over had been effected from 2 parallel flows to 4, from 4 to 6 and from 6 to 8 tubes.

Looking at the velocity curve it is clearly shown where the various steps have been made.

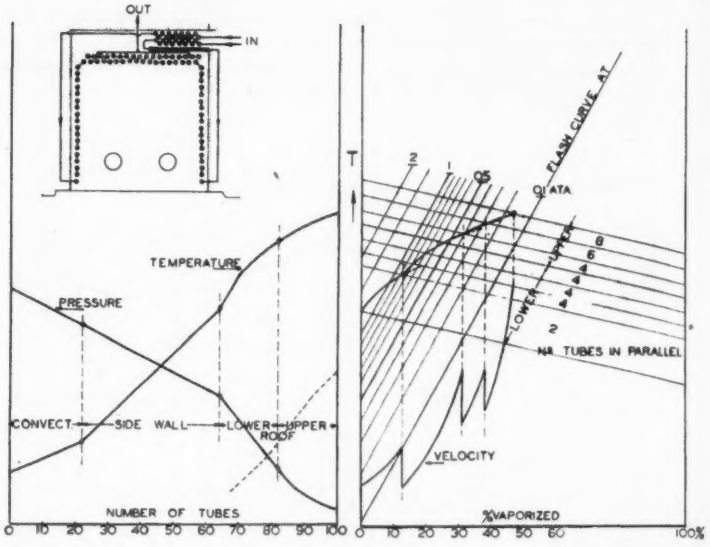


FIG. 14.

FURNACE FOR HIGH VACUUM PLANT II.

Conspicuous in this case is the temperature–vaporization curve which varies with each sectional enlargement of the tubes.

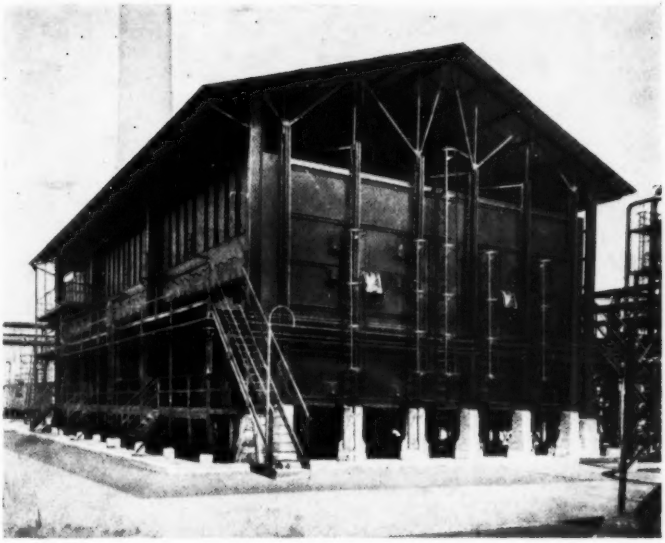
In this way a uniform rise of temperature up to the furnace outlet has been achieved.

The object of this paper is to draw attention to a subject regarding which little is to be found in the reference literature.

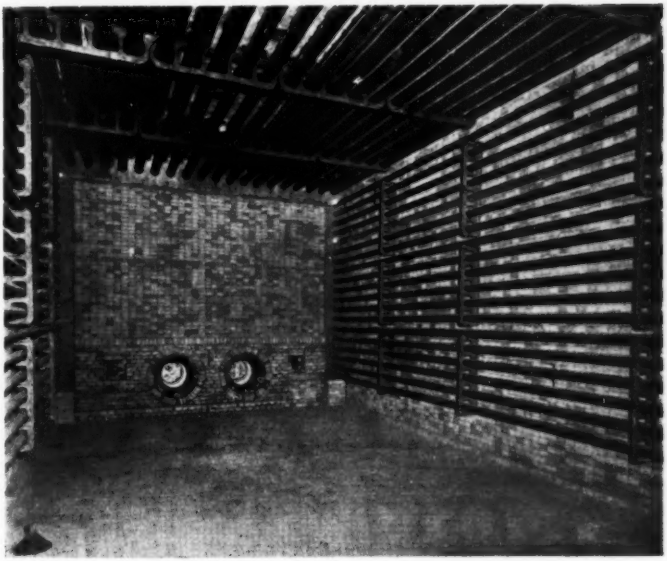
Some of the points discussed may be of interest to both the furnace designer and the chemical engineer.

DISCUSSION.

THE CHAIRMAN : Mr Baars has referred to the very short zone where there is froth present and to the formation of bubbles which float to the top of the tube, giving rise to a serious possibility of burning. I wonder whether, owing to the high velocity occurring in this section of the still, the bubbles are not carried forward. A further point is that if bubbles are present they will be in the top of the tube probably, and almost certainly in the radiant section, because it is in the last tubes of the furnace that the



LUMMUS FURNACE.



INTERIOR OF ONE SECTION OF A LUMMUS FURNACE.

[*To face p.* 436.

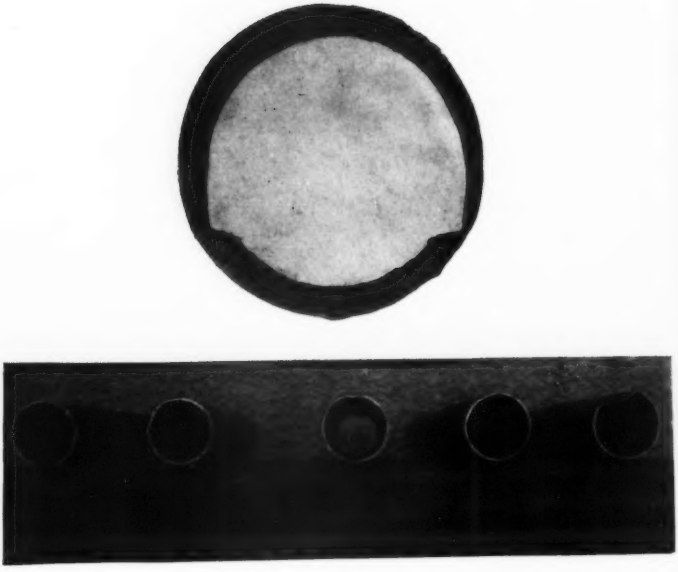


FIG. 13.
RESULTS OF EROSION AND CORROSION

vaporization occurs. Thus, they should not be exposed directly to radiation.

In connexion with the later stages in the vaporization, where mist formation occurs, one would expect that an appreciable proportion of the mist would be thrown out on going round the return bend, in a manner somewhat similar to that which happens in the feeding of gasoline–air mixture from a manifold into the engine. Thus, there would be a liquid film present in such parts of the still which would alter the rate of heat transfer.

MR G. BAARS : The Mechanical Laboratory at Delft has specially made a model of tubes which can be fixed in various positions in order to study the behaviour of the bubbles when liquid and gas are pumped through simultaneously. In the paper reference is made to lectures discussing the results of these investigations which were published in *De Ingenieur*, 1939, Nos. 4 and 21, and in which photographs show how the bubbles are flowing with various velocities of the liquid. These bubbles are not following a definite rule. In a vertical tube for instance where the liquid is going down, the bubbles may go upwards or downwards depending on the size of the tube and the velocity of the liquid. They may even come temporarily to a standstill and collect other bubbles until the tube area is almost closed by the size of the bubbles. Similar situations may occur in furnace tubes, especially horizontal ones which may have been bent upward due to some superheating. Usually the velocity in the furnace tubes, where vaporization starts, is not so high that the bubbles are forced to follow the liquid with the same velocity. In practice there are definite indications that vapour and liquid are separating inside the furnace tubes.

In connexion with the Chairman's other question as to whether liquids will be thrown out at the return bends, we may assume that this is so; the so-called mist extractor works on that principle. I have stated that, when liquid is vaporizing in the mist condition, small drops of liquid will touch the wall and will vaporize. When the direction of flow is changed as in the return bends there will be more liquid on the outward side of the return bend and the heat transfer will change. However, this separation will be of short duration due to the turbulence in the return bends. This has been proved by the fact that cavitation or erosion is usually shown in the return bend and over a length of about 1 ft at the entrance of the next tube.

DR R. C. FISHER : I would like to ask Mr Baars the following question. In his calculations for pressure drop, the conditions at the outlet of the transfer line control the whole problem—pressure gradient, temperature gradient, and vaporization. I wonder whether the conditions at the transfer line where it enters the flash zone are identical with the conditions existing in the flash zone, in particular the pressure. In other words, can it be safely assumed that in the mouth of transfer line a pressure is reached which is identical with the pressure in the flash zone, or is it higher? We know that when gases are discharged from a pressure vessel through a simple orifice, the pressure in the orifice is some 50 to 60 per cent of the upstream pressure, independent of the downstream pressure (critical pressure ratio !). On the other hand when the discharge orifice is fitted

with a well-rounded nozzle or venturi pipe it is possible to approximate or to reach the downstream pressure. It seems to me that discharge from a coil system as existing in a tube-still may be governed by similar principles as control discharge from sharp-edged orifices and venturi nozzles.

This question as to what is the true discharge pressure, has arisen in connexion with similar calculations as outlined by Mr Baars. When computing pressure drop with pressure-stills, actual plant data can be satisfactorily verified, whereas it is often extremely difficult to get a good check with vacuum tube-stills.

MR BAARS : Of course there will be difference in pressure between the outlet of the transfer line and the vaporizing section of the fractionating column, but I would always regard it as safe to assume that the pressure at the transfer-line outlet will be the same as the pressure in the fractionating column so that we may ignore the pressure drop there, besides this we have made so many assumptions that for practical purposes we are on the safe side.

MR. B. S. BRAILEY : One question I would like to put is in connexion with the answer already given to the Chairman concerning the bubbles collecting in the top of the tube. In the paper on page 433, Mr Baars states that " In order to ensure good heat transmission in the vaporizing zone it is essential that the inner side of the tube walls be kept wet," his assumption being that, provided there is enough liquid in the tube, the liquid would " flow along the wall of the tube." Apart from the question of how that could be brought about, and even supposing it were possible, it is still not clear in what way the heat transfer could be improved, since, after the heat has passed through the oil film, it still has to pass through the film of vapour which is flowing in the middle of the tube.

In the paper, just above Fig. 3, Mr Baars states : " The average load of a furnace combustion chamber is 7,000 to 14,000 B.Th.U/cu. ft/hr whereas this load for boilers has already reached a figure up to 280,000 B.Th.U/cu. ft." I wonder if the word " already " was actually meant or did it just slip in, because it would rather indicate that boilers are much ahead of the oil furnaces, whereas some of us prefer to believe that the reverse is the case, since it was the oil furnace people who started circulating the oil through the tubes by pumping, and the boiler people are just beginning to follow suit.

Again, the real reason why a difference in rates of heat transfer exists and will continue to exist is that the temperature of the oil film must be kept within certain limits in order to prevent coking difficulties creeping in.

On page 433 there is the statement : " It is recommended that the thermometer controlling the temperature of the furnace outlet should not be placed at the furnace outlet, but should be located at the place where vaporization commences." I do not say that I disagree entirely; indeed, many people would subscribe to this view, but the point I should like to emphasize is that it is only an expression of opinion and not a statement of fact; and when it comes to an expression of opinion, I personally am inclined to believe that the thermometer should be located at the outlet from the furnace because, as far as the plant operation is concerned, the

temperature of the fluid which the operator must have at the inlet to his column is that of the outlet from the furnace. When it comes to the behaviour of the furnace itself, the intermediate temperature depends on the air and steam and fuel and what not; and although the operator may be well advised to keep his eye on the intermediate temperature in the furnace, in the final analysis what he wants the controller to do is to ensure that the oil or the fluid at the *outlet* of the furnace is maintained at the correct temperature.

MR. BAARS : I have stated that in order to ensure good heat transmission in the vaporizing zone, it is essential that the inner side of the tube walls be kept wet. To give an idea about the amount of liquid that is present when 70 per cent of the oil is vaporized I have made the assumption that when all the liquid would flow along the wall of the tube the thickness of the film would then be about 1/80 in. This does not mean that all the liquid is actually flown along the tube wall.

Regarding the next point about comparison between boilers and furnaces, I would not say that boiler constructions are ahead of oil-heater constructions, but we may still learn from each other, although the conditions in regard to steam boilers are different from those relating to oil heaters. With steam boilers they usually work up to the highest efficiency whereas for oil furnaces they are never going to the extremes because safe operation and low maintenance costs are one of the essential factors. The high heat load I have mentioned is for the combustion chamber of the La Mont boiler, which is a boiler with forced circulation. In the Stratford heater, such as that at Lobitos, the heat load of the combustion chamber would surely be higher than the figures I mentioned as representing the average rate for oil furnaces.

When Mr Brailey repeats, " It is recommendable that the control of the temperature of the furnace outlet should not be placed in the furnace outlet, but should be located where vaporization commences," I may refer to the cases for which I had recommended following this practice, that is, for such furnaces where the temperature of the oil in the vaporizing section follows a continuous fall towards the outlet of the furnace. In such cases it is advisable to control the furnace outlet temperature with the temperature located at the place where vaporization starts, because there the temperature may vary more. The temperature recorder still remains at the furnace outlet.

MR D. A. C. DEWDNEY : We are all thankful to Mr Baars for his interesting paper.

The placing of the lines of constant heat content depends on the accuracy with which the distribution of heat load throughout the furnace is estimated. Are there any difficulties in that connexion? How critical is accurate estimation of the heat-load distribution to the method?

MR BAARS : I may refer to the slides I have shown indicating the heat distribution in furnaces in operation, from which it is clear that even in a properly designed furnace the heat distribution can be changed by changing the direction of the burners. We have also seen how the unequal heat absorption was effected by eccentrically covering of the floor tubes.

I think the main factors influencing the heat distribution are well known at the moment, so that in practice the most economical distribution can be obtained.

With regard to the temperature–vaporization curve only the lines of equal heat content will change by variations in heat distribution involving no big changes in the pressure drop of the furnace.

MR W. D. HARDY: My question is of a purely practical nature.

In the distillation of coal tar in tube stills, the tendency of recent Continental practice has been to operate the whole of the tube system under pressure by throttling at the outlet.

By this means the degree of vaporization in the tubes is depressed, and the tubes have been said to have a longer life—failure being largely due to the erosive action of vapours moving at high speeds.

Can Mr Baars express an opinion on this practice?

MR BAARS: Is it true that you like to know whether there is a certain velocity limit for corrosion?

MR HARDY: Yes.

MR BAARS: Going to high velocities more damage will be done due to corrosion and erosion in case the material processed is of corrosive nature, and I confirm that there is really a practical limit. This limit has to be investigated for each material processed separately.

A SPEAKER: Would you use a throttling valve?

MR BAARS: A throttling valve in a distillation furnace outlet is not recommendable, especially not in the application I have discussed this evening. I am not talking about cracking furnaces. To promote vaporization in the furnace tubes in order to absorb full heat of vaporization and to reduce the temperature it will be wrong to make any restrictions of the flow at the furnace outlet. As already explained I would not have any objections to use a throttling valve at the point where vaporization starts in order to avoid foam formation so that the liquid will be atomized through the valve opening and will be transferred into the mist condition.

MR A. D. DAVIDSON: I should like to ask Mr Baars how he estimated his vaporization at 70 per cent when he assumes the wetting of the wall to be 1/80 in. Has he assumed that the vapour is moving at the same velocity as the liquid, and if so, at what velocity?

He quotes a figure of from 5 to 8 B.Th.U/sq.ft/°F/hr for the k value in the convection section of a tube still. Does he include in that figure the heat absorbed by radiation in the top row of convection tubes?

On the question of foam and its viscosity, how would he estimate the viscosity of the foam? Would he come to a pseudo viscosity by blending the viscosities of vapour and liquid?

MR BAARS: I cannot answer Mr. Davidson's first question more fully than I have already done by saying it is my personal feeling that maximum

70 per cent by weight should be vaporized in the furnace. For a specific case it will be easy to calculate the velocity at the furnace outlet because at that point the conditions are very well known.

With regard to the k value for heat transfer in the convection section of a furnace, I have not included any radiant heat. For those rows of tubes receiving radiant heat in addition, the radiant heat absorbed should be calculated separately. I have not gone into the question of the velocity of foam because in most of the furnaces the foam condition is of short duration, and it does not play an important part in the pressure drop of the furnace. Prof Einstein has a formula for calculating the viscosity of liquid–vapour mixtures, but I did not make use of this formula in order to keep the calculation simple.

MR M. B. DONALD: When one considers the fundamentals of the evaporation of liquids by heating them in tubes—I could quote Macadam's book on Heat Transmission, for example—one finds that, as the heat load increases, the evaporation increases up to a point and then suddenly falls away. The reason for the falling away of the evaporation is that there is formed what is known as a "Leiden frost" or spheroidal effect on the surface, *i.e.*, the surface becomes covered with a layer of vapour. It has been postulated here that a very thin film of oil is on the tube surface, but I very much doubt whether that is the case in conditions where you have very high heat load.

I would also like to ask Mr Baars how he calculated his pressure drop by means of the Fanning equation. The equation reduces to how F is determined in practice.

MR BAARS: I am sorry that I have not found in Macadam's book that as the heat load increases the vaporization increases up to a point and then suddenly falls away. What I found under the heading "heat transfer to boiling liquids" on page 331 was: "As shown in Fig. 178 with moderate temperature differences as the fluid is progressively vaporized, the local overall coefficient at first increases, goes through a maximum, and then decreases sharply toward values typical of superheating dry vapor," and this is in line with what I have mentioned in my paper.

As I have said, a series of lectures on the flow of liquid and gas have been delivered in Delft, and I have prepared my paper as an addition to these. This is the reason why I have not gone back to fundamentals. Macadam's book gives everything about the factor f to be used in the Fanning equation. I have taken the f according to Fig. 51 on page 118 for smooth inside tubes to calculate the pressure drop.

THE CHAIRMAN put a question which had been submitted by MR R. E. JOHNSTONE as follows:

Referring to Fig. 12 could Mr Baars give us any information about the rate of charge to this furnace, also the length and internal diameter of the tubes?

This information will probably be of general interest in the case of every example, for it would enable a comparison to be made with existing furnaces.

MR BAARS: I have calculated that furnace, and I will give you the figures later on.

The rate of charge to the furnace was 330 tons per day. The length of the tubes is 24 ft and the inside diameters are, respectively, $2\frac{3}{4}$ and $5\frac{1}{4}$ in.

On the motion of the Chairman, a hearty vote of thanks was accorded Mr Baars for his paper; and the Chairman commented that so large an attendance at the meeting, in spite of the very bad weather prevailing, was in itself a tribute to Mr Baars. Furthermore in spite of the intensely cold room, due to a breakdown in the heating apparatus, most of the audience had remained for the discussion. Both of these were a tribute to the author for his paper and for his interesting replies to the discussion.

OBITUARY.

MR. W. H. PARK.

It is with very deep regret that we have to record the death of Mr W. H. Park. Mr Park was a distinguished student of Glasgow Technical College, and received his early training with Fairfield Engineering Company, Govan.

In 1936 he took up the position of Chief Draughtsman with the Pulsometer Engineering Company. He later joined the Staff of "Shell" Refining and Marketing Co. Ltd., with whom he was Chief Draughtsman, first at Heysham and later at Ince Hall. During the war years he was actively engaged on the various pipeline projects for the Petroleum Warfare Department and also the FIDO Installation. He successfully tackled the many pumping problems in these schemes, and by his zeal and energy contributed greatly to the speedy and efficient handling of these projects in the drawing office.

After the war Mr Park was transferred to the engineering staff of the same company, which position he held up to the time of his death. He was elected a Member of the Institute in 1945, and was an Associate Member of the Institution of Mechanical Engineers.

Mr Park is survived by his widow and one daughter to whom we extend our deepest sympathy.